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Lower Klamath Watersheds LiDAR & Digital Imagery

Technical Data Report Summary

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Cover Photo: View looking west at a partially scorched hillside located south of Marble Mountain Ranch. The image was created from the gridded LiDAR surface overlaid with the 3D LiDAR point cloud 4-band digital imagery.

INTRODUCTION

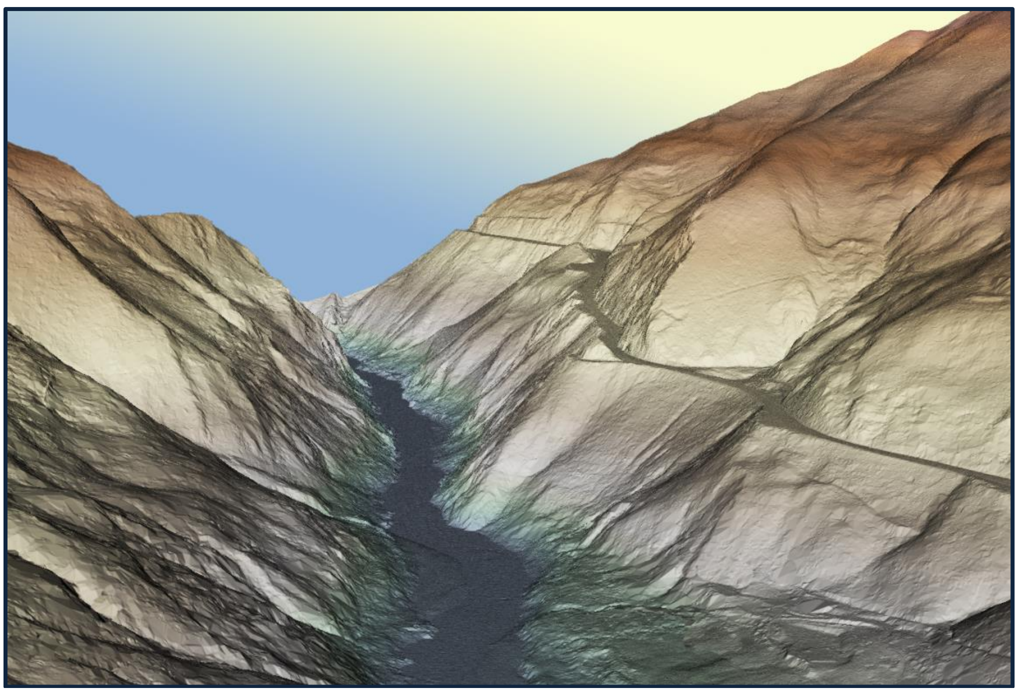
This photo taken by QSI acquisition staff shows a view of static acquisition equipment set up on site for the Lower Klamath Watersheds project in California.

In November 2013, Quantum Spatial (QSI) was contracted by the Mid Klamath Watershed Council (MKWC) to collect Light Detection and Ranging (LiDAR) data and digital imagery in the early spring of 2014 for the Lower Klamath Watersheds project in California. The Lower Klamath Watersheds project includes three main areas of interest (AOIs); the Ishi Tap Watershed AOI, the Lower Klamath River Corridor AOI, and the Additional Watersheds AOI. QSI delivered the initial priority areas on June 6th, 2014, followed by the Ishi Tap Watershed AOI on July 25th, 2014, and the Lower Klamath River Corridor on May 5th, 2015. This final data delivery includes the Additional Watersheds area of interest (contract # 13-C-22, modification #2) as well as all previously delivered LiDAR data. Data were collected to aid MKWC in assessing the topographic and geophysical properties of the study area to support restoration activities on the Lower Klamath River and surrounding watersheds.

This report summarizes all delivered LiDAR data and imagery, and accompanies the final delivery of all processed LiDAR data for the project. Documented herein are contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including LiDAR accuracy and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to MKWC is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected on the Lower Klamath Watersheds site

Project Site	Delivered Acres	Acquisition Dates	Data Type
Preliminary Delivery – 2014 Priority Areas	19,380	03/24/2014	LiDAR
		03/23/2014	4 band (RGB-NIR) Digital Imagery
Delivery 1 – Ishi Tap Watershed AOI	52,432	05/12/2014, 05/13/2014, 05/16/2014, 05/17/2014 & 05/21/2014	LiDAR
Delivery 2 – Lower Klamath River Corridor AOI	56,289	12/30/2014 – 01/05/2015, 01/13/2015, & 03/27/2015	LiDAR
		03/23/2014	4 band (RGB-NIR) Digital Imagery
Delivery 3 – Additional Watersheds AOIs	35,394	05/23/2015 – 05/26/2015	LiDAR



This image shows a view looking west over the Klamath River located on the southeast base of Sarvorum Mountain. The image was created from the gridded LiDAR surface and colored by elevation.

Deliverable Products

Table 2: Products delivered to MKWC for the Lower Klamath Watersheds site

Lower Klamath Watersheds Products	
Projection: UTM Zone 10 Horizontal Datum: NAD83 (CORS96)* Vertical Datum: NAVD88 (GEOID09) Units: Meters	Projection: California State Plane Zone 1 Horizontal Datum: NAD83 (CORS96)* Vertical Datum: NAVD88 (GEOID09) Units: US Survey Feet
Points	LAS v 1.2 • All Returns • Ground Returns
Rasters	1.0 Meter ESRI Grids (UTM) • Bare Earth Model • Highest Hit Model 3.0 Foot ESRI Grids (CASP) • Bare Earth Model • Highest Hit Model 0.5 Meter GeoTiffs (UTM) • Intensity Images 1.5 Foot GeoTiffs (CASP) • Intensity Images
Vectors	Shapefiles (*.shp) • Site Boundary • LiDAR/DEM Tile Indices • Orthoimagery Tile Index (Delivered May 5th, 2015)
Digital Imagery	30 cm GeoTiffs (Delivered May 5th, 2015) • 4 Band Imagery Mosaics (RGB-NIR) – Applicable to the Lower Klamath Corridor AOI Only

**The data were created in NAD83 (CORS96), but for GIS purposes are defined as NAD83 (HARN) as per client specifications.*

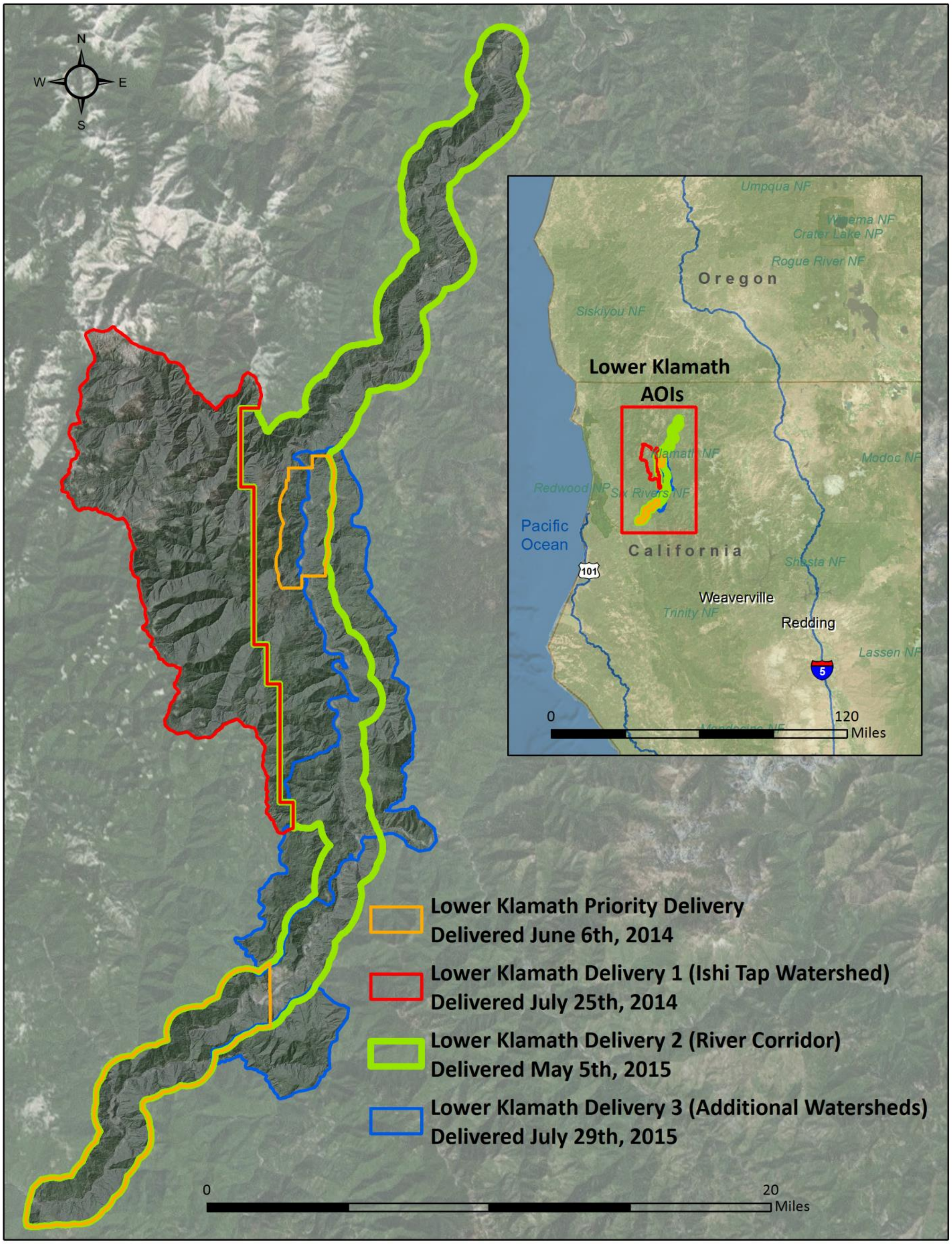


Figure 1: Location map of the Lower Klamath Watersheds sites in California

Acquisition

QSI's Cessna Caravan

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Lower Klamath Watersheds LiDAR study area at the target point density of ≥8.0 points/m^2 (0.74 points/ft^2). Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all leaf-off or low-flow contract specifications.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access and potential air space restrictions were reviewed.

Airborne Survey

LiDAR

The LiDAR survey was accomplished using a Leica ALS50, ALS70, or ALS80 system mounted in QSI aircraft. Table 3 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Lower Klamath Watersheds project area. The Leica ALS50 laser system records up to four range measurements (returns) per pulse. The Leica ALS70 and ALS80 laser systems can record unlimited range measurements (returns) per pulse, but typically do not record more than 5 returns per pulse. It is not uncommon for some types of surfaces (e.g., dense vegetation or water) to return fewer pulses to the LiDAR sensor than the laser originally emitted. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset.

Table 3: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications				
AOI	**Priority Areas**	**Ishi Tap Watershed**	**Lower Klamath River Corridor**	**Additional Watersheds**
Acquisition Dates	03/24/2014	05/12/2014, 05/13/2014, 05/16/2014, 05/17/2014, 05/21/2014	12/30/2014 – 01/05/2015, 01/13/2015, 03/27/2015	05/23/2015 – 05/26/2015
Aircraft Used	Partenavia	Cessna 208B	Partenavia & Cessna 208B	Cessna 208B
Sensor	Leica ALS70	Leica ALS50	Leica ALS70 & ALS80	Leica ALS70
Survey Altitude (AGL)	1,300 m	900 m	1,200 – 1,300 m	Varies
Target Pulse Rate	170 - 199 kHz	106 kHz	190 - 230 kHz	172 kHz
Pulse Mode	Single Pulse in Air (SPiA)	Single Pulse in Air (SPiA)	Single Pulse in Air (SPiA)	Single Pulse in Air (SPiA)
Laser Pulse Diameter	30 cm	21 cm	28 - 30 cm	varies
Mirror Scan Rate	41.7 Hz	54 Hz	40 - 55 Hz	39.0 Hz
Field of View	30°	28°	30°	24°
GPS Baselines	≤13 nm	≤13 nm	≤13 nm	≤13 nm
GPS PDOP	≤3.0	≤3.0	≤3.0	≤3.0
GPS Satellite Constellation	≥6	≥6	≥6	≥6
Maximum Returns	Unlimited, but typically not more than 5	4	Unlimited, but typically not more than 5	Unlimited, but typically not more than 5
Intensity	8-bit	8-bit	8-bit	8-bit
Resolution/Density	Average 8 pulses/m^2	Average 8 pulses/m^2	Average 8 pulses/m^2	Average 8 pulses/m^2
Accuracy	$RMSE_Z$ ≤ 15 cm	$RMSE_Z$ ≤ 15 cm	$RMSE_Z$ ≤ 15 cm	$RMSE_Z$ ≤ 15 cm

All areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the LiDAR data collection mission. Position of the aircraft was measured twice per second (2 Hz) by an onboard differential GPS unit, and aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft and sensor position and attitude data are indexed by GPS time.

This photo taken by QSI acquisition staff shows a view of static ground survey equipment set up on a hillside overlooking the Lower Klamath River.

Digital Imagery

Aerial imagery was collected using an UltraCam Eagle 260 megapixel digital camera (Table 4) mounted in a Cessna Caravan. The UltraCam Eagle is a large format digital aerial camera manufactured by Microsoft Corporation. The system is gyro-stabilized and simultaneously collects panchromatic and multispectral (RGB, NIR) imagery. Panchromatic lenses collect high resolution imagery by illuminating nine charge coupled device (CCD) arrays, writing nine raw image files. RGB and NIR lenses collect lower resolution imagery, written as four individual raw image files. Level 2 images are created by stitching together raw image data from the nine panchromatic CCDs and are ultimately combined with the multispectral image data to yield Level 3 pan-sharpened TIFFs.

Table 4: Camera manufacturer's specifications

UltraCam Eagle	
Focal Length	80 mm
Data Format	RGB NIR
Pixel Size	5.2 µm
Image Size	20,010 x 13,080 pixels
Frame Rate	1.8 seconds
FOV	66° x 46°

For the Lower Klamath Watersheds site, images were collected in four spectral bands (red, green, blue, and NIR) with 60% along track overlap and 30% sidelap between frames. The acquisition flight parameters were designed to yield a native pixel resolution of ≤ 15 cm, which exceeds the minimum requested orthophoto scale of 30 cm. The resulting spatial accuracies (RMSE) were routinely ≤45 cm at 95% confidence level. Orthophoto specifications particular to the Lower Klamath Watersheds project are in Table 5.

Table 5: Project-specific orthophoto specifications

Digital Orthophotography Specifications	
Equipment	UltraCam Eagle
Spectral Bands	Red, Green, Blue, NIR
Resolution	30 cm pixel size
Along Track Overlap	≥60%
Flight Altitude (MSL)	14,710 – 15,474 meters
GPS Baselines	≤25 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Horizontal Accuracy	0.06 m

Ground Control

Ground control surveys, including monumentation, aerial targets and ground survey points (GSPs), were conducted to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data and orthoimagery products.

Existing DOT Monument

QSI-Established Monument

Monumentation

The spatial configuration of ground survey monuments provided redundant control within 13 nautical miles of the mission areas for LiDAR flights. Monuments were also used for collection of ground survey points using real time kinematic (RTK) and post-processed kinematic (PPK) survey techniques.

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. QSI utilized seven existing monuments and established three new monuments for the Lower Klamath Watersheds LiDAR project (Table 6, Figure 2). New monumentation was set using 5/8” x 30” rebar topped with stamped 2" aluminum caps. QSI’s professional land surveyor, Christopher Glantz (CAPLS#8850) oversaw and certified the establishment of all monuments.

Table 6: Monuments established for the Lower Klamath Watersheds acquisition. Coordinates are on the NAD83 (HARN) datum

Monument ID	Latitude	Longitude	Ellipsoid (meters)
DH6356	41° 17' 00.55317"	-123° 34' 35.35659"	130.119
DH6357	41° 18' 26.74622"	-123° 31' 40.34642"	119.445
DF4526	41° 31' 32.43289"	-123° 31' 35.44748"	197.692
DH6353	41° 14' 25.69381"	-123° 39' 20.34298"	99.143
ISHI_01	41° 32' 01.47086"	-123° 35' 10.27245"	1034.683
ISHI_02	41° 32' 03.72701"	-123° 38' 56.09394"	1523.188
ISHI_03	41° 26' 02.84636"	-123° 33' 42.36801"	1179.968
DH6613	41° 28' 11.76028"	-123° 29' 59.81055"	215.369
DH6609	41° 35' 30.92371"	-123° 30' 38.13352"	228.742
DH6610	41° 43' 47.83116"	-123° 25' 46.38076"	273.947

To correct the continuously recorded onboard measurements of the aircraft position, QSI concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) over each monument. During post-processing, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

[1] OPUS is a free service provided by the National Geodetic Survey to process corrected monument positions. http://www.ngs.noaa.gov/OPUS.

Monuments were established according to the national standard for geodetic control networks, as specified in the Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards for geodetic networks.[2] This standard provides guidelines for classification of monument quality at the 95% confidence interval as a basis for comparing the quality of one control network to another. The monument rating for this project is shown in Table 7.

Table 7: Federal Geographic Data Committee monument rating for network accuracy

Direction	Rating
1.96 * St Dev $_{NE}$:	0.050 m
1.96 * St Dev $_{z}$:	0.050 m

For the Lower Klamath Watersheds LiDAR project, the monument coordinates contributed no more than 7.1 cm of positional error to the geolocation of the final ground survey points and LiDAR, with 95% confidence.

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic and post-processed kinematic (PPK) survey techniques. A Trimble R7 or R8 base unit was positioned at a nearby monument to broadcast a kinematic correction to a roving Trimble R8 GNSS receiver. All GSP measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. When collecting RTK and PPK data, the rover records data while stationary for five seconds, then calculates the pseudorange position using at least three one-second epochs. Relative errors for any GSP position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted. See Table 8 for Trimble unit specifications.

GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. GSP measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. GSPs were collected within as many flightlines as possible; however the distribution of GSPs depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 2).

Table 8: Trimble equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2 RoHS	TRM57971.00	Static
Trimble R8	Integrated Antenna R8 Model 2	TRM_R8_GNSS	Static, Rover

[2] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.2-1998). Part 2: Standards for Geodetic Networks, Table 2.1, page 2-3. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2

Aerial Targets

Aerial targets were placed throughout the Lower Klamath River Corridor project area prior to imagery acquisition in order to geo-spatially correct the orthoimagery. Located within RTK range of the ground survey monuments, the targets were secured with surveyor's nails and routinely checked for disturbance (Figure 2).

The air targets used for the Lower Klamath Watersheds project were white and black vinyl squares approximately 115 cm in size. Each target was precisely located using five RTK points (four corner points and a center point).

This photo taken by QSI acquisition staff shows a view of ground survey point collection setup using static GNSS equipment over monument DF4526.

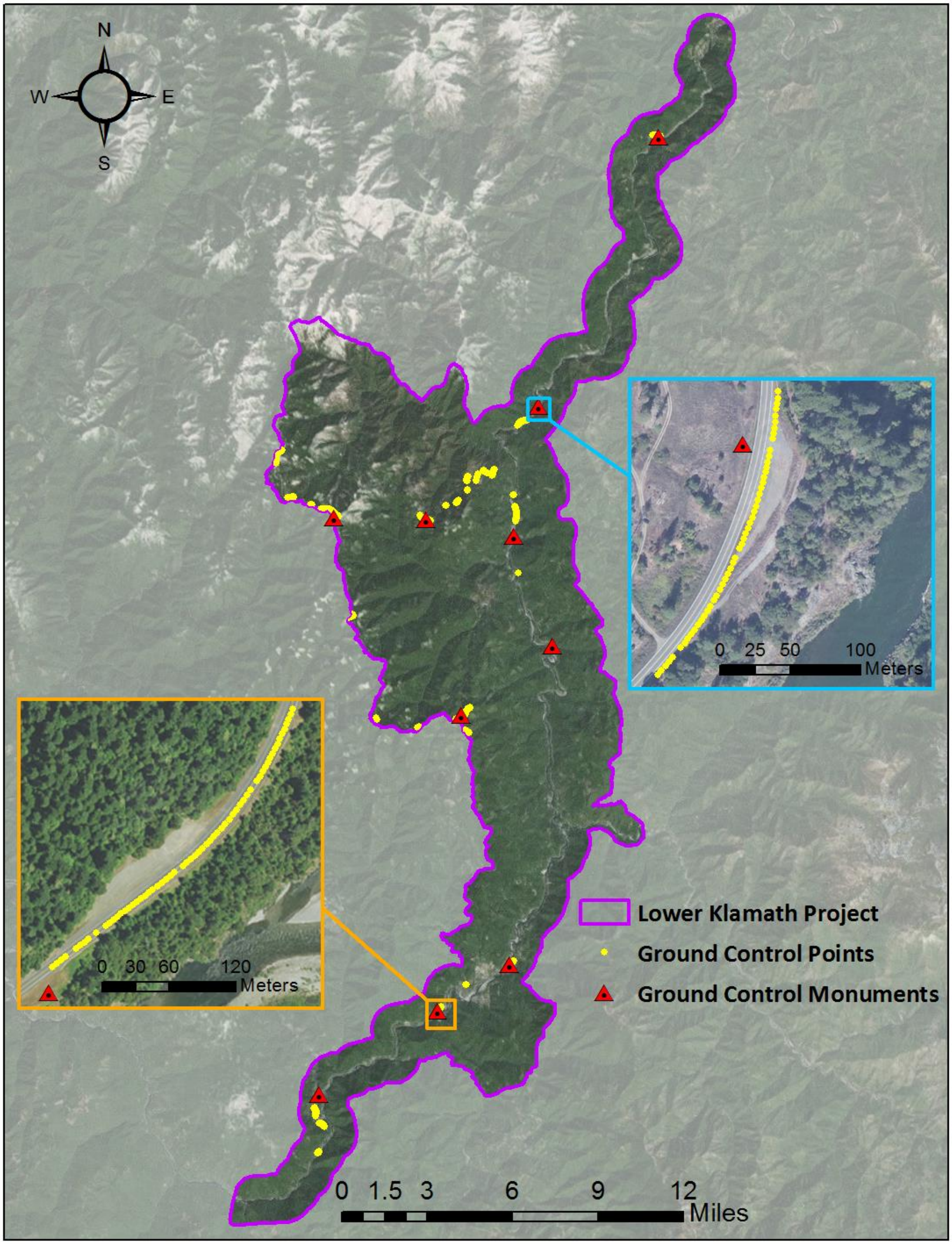
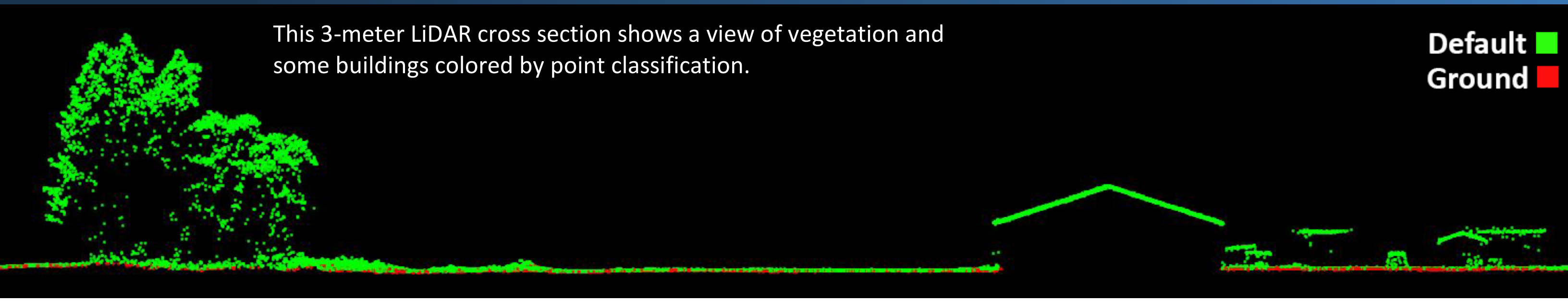


Figure 2: Ground control location map



This 3-meter LiDAR cross section shows a view of vegetation and some buildings colored by point classification.

LiDAR Data

Upon completion of data acquisition, QSI processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and LiDAR point classification (Table 9). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 10.

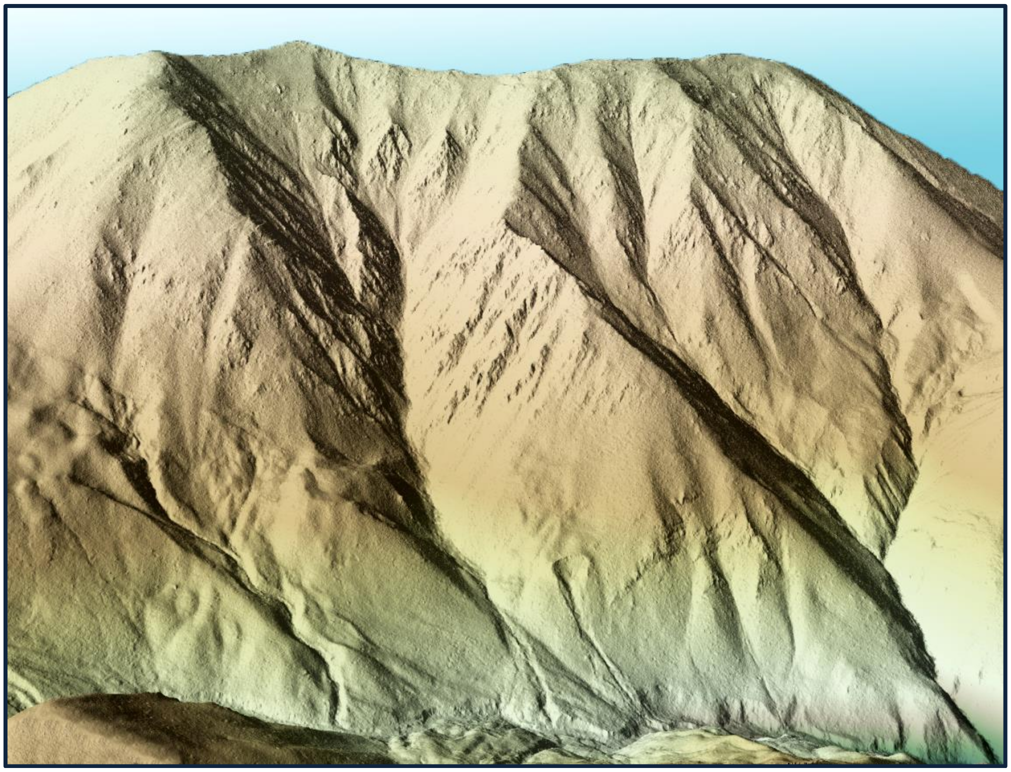
Table 9: ASPRS LAS classification standards applied to the Lower Klamath Watersheds dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and man-made structures
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms

Table 10: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	IPAS TC v.3.1 Waypoint Inertial Explorer v.8.5
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.2) format. Convert data to orthometric elevations by applying a geoid correction.	ALS Post Processing Software v.2.75 Waypoint Inertial Explorer v.8.5 Leica Cloudpro v. 1.2.1

LiDAR Processing Step	Software Used
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.14 & v.15
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	TerraMatch v.14 & v.15
Classify resulting data to ground and other client designated ASPRS classifications (Table 9). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.14 & v.15 TerraModeler v.14 & v.15
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as ESRI GRIDs at 1 meter and 3.0 foot pixel resolutions.	TerraScan v.14 & v.15 TerraModeler v.14 & v.15 ArcMap v. 10.1
Export intensity images as GeoTIFFs at 0.5 meter and 1.5 foot pixel resolutions.	TerraScan v.14 & v.15 TerraModeler v.14 & v.15 ArcMap v. 10.1



View of Dillon Divide looking northwest. This image was created from the gridded LiDAR surface colored by elevation.

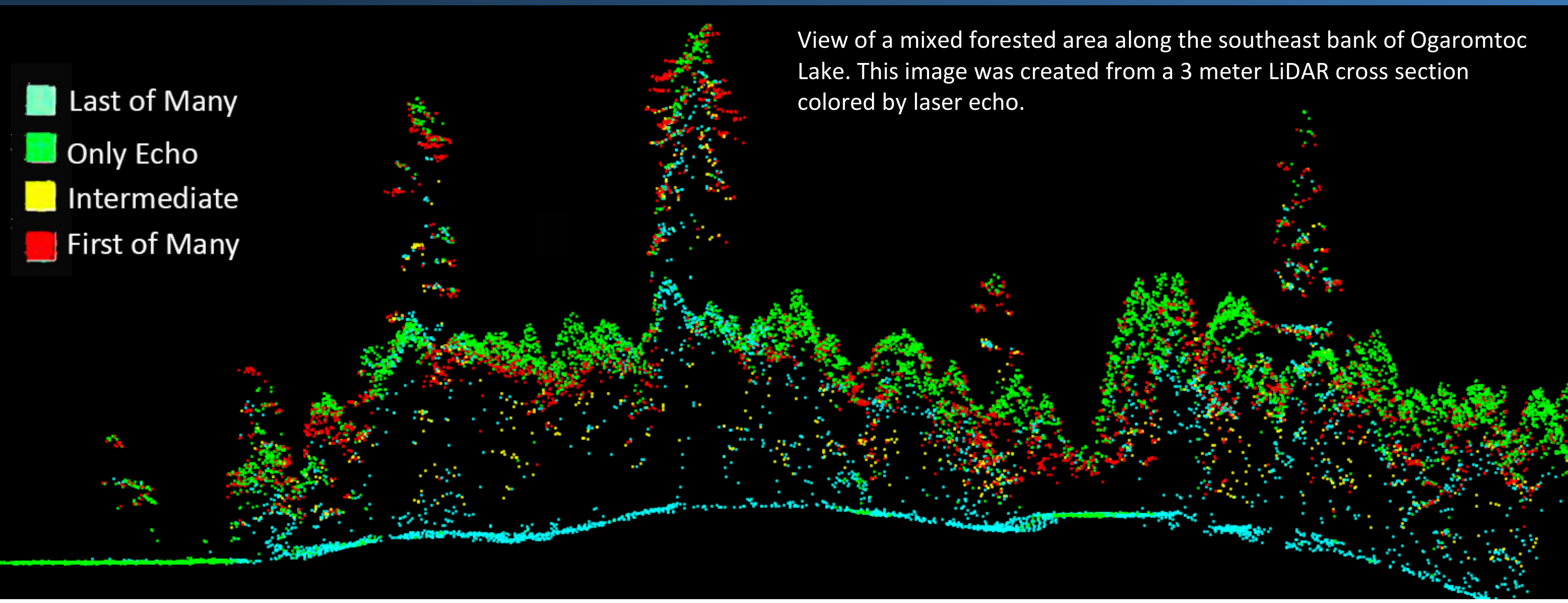
Digital Imagery

As with the NIR LiDAR, the collected digital photographs went through multiple processing steps to create final orthophoto products. Initially, image radiometric values were calibrated to specific gain and exposure settings. Photo position and orientation were then calculated by linking the time of image capture to the smoothed best estimate of trajectory (SBET) file created during LiDAR post-processing. Within Leica Photogrammetry Suite (LPS), an automated aerial triangulation was performed to tie images together and adjust the photo block to align with ground control.

Adjusted images were orthorectified using the LiDAR-derived ground model to remove displacement effects from topographic relief inherent in the imagery and individual orthorectified TIFFs were blended together to remove seams. The final mosaics were corrected for any remaining radiometric differences between images using Inpho's OrthoVista. The processing workflow for orthophotos is summarized in Table 11.

Table 11: Orthophoto processing workflow

Orthophoto Processing Step	Software Used
Resolve GPS kinematic corrections for the aircraft position data using kinematic aircraft GPS (collected at 2 HS) and static ground GPS (1 Hz) data collected over geodetic controls.	POSPac MMS v. 6.1
Develop a smooth best estimate trajectory (SBET) file that blends post-processed aircraft position with attitude data. Sensor heading, position, and attitude are calculated throughout the survey.	POSPac MMS v. 5.4
Create an exterior orientation file (EO) for each photo image with omega, phi, and kappa.	POSPac MMS v. 6.1
Convert Level 00 raw imagery data into geometrically corrected Level 02 image files.	UltraMap 2.3.2
Apply radiometric adjustments to Level 02 image files to create Level 03 Pan-sharpened TIFFs.	UltraMap 2.3.2
Apply EO to photos, measure ground control points and perform aerial triangulation.	LPS 2013
Import DEM, orthorectify and clip triangulated photos to the specified area of interest.	LPS 2013
Mosaic orthorectified imagery, blending seams between individual photos and correcting for radiometric differences between photos.	Inpho v. 5.5



View of a mixed forested area along the southeast bank of Ogaromtoc Lake. This image was created from a 3 meter LiDAR cross section colored by laser echo.

LiDAR Density

First Return Point Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m^2 (0.74 points/ft^2). First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser. First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The average first-return density of LiDAR data for each of the AOIs in the Lower Klamath Watersheds project is displayed in Table 12. The statistical and spatial distributions of first return densities and per 100 m x 100 m cell are portrayed in Figure 3 through Figure 7.

Table 12: Average First Return LiDAR point densities

Classification	Point Density			
	Priority Areas	Ishi Tap Watershed	Lower Klamath River Corridor	Additional Watersheds
First-Return	1.05 points/ft^2 11.28 points/m^2	1.18 points/ft^2 12.66 points/m^2	2.00 points/ft^2 21.55 points/m^2	1.62 points/ft^2 17.41 points/m^2

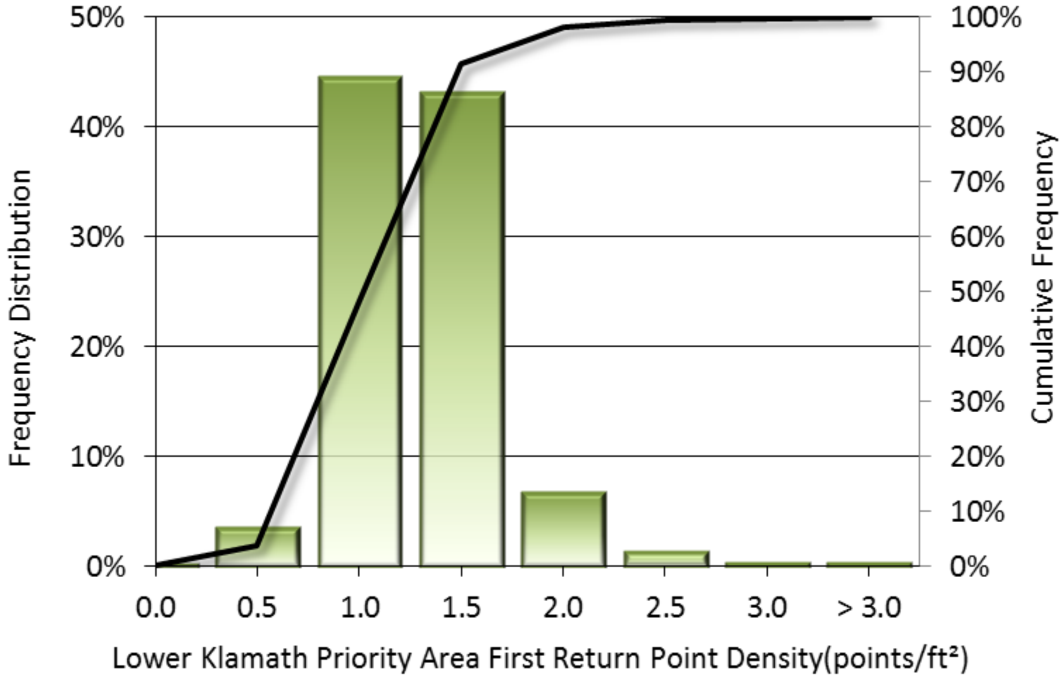


Figure 3: Frequency distribution of first return densities per 100 x 100 m cell in the Priority AOIs

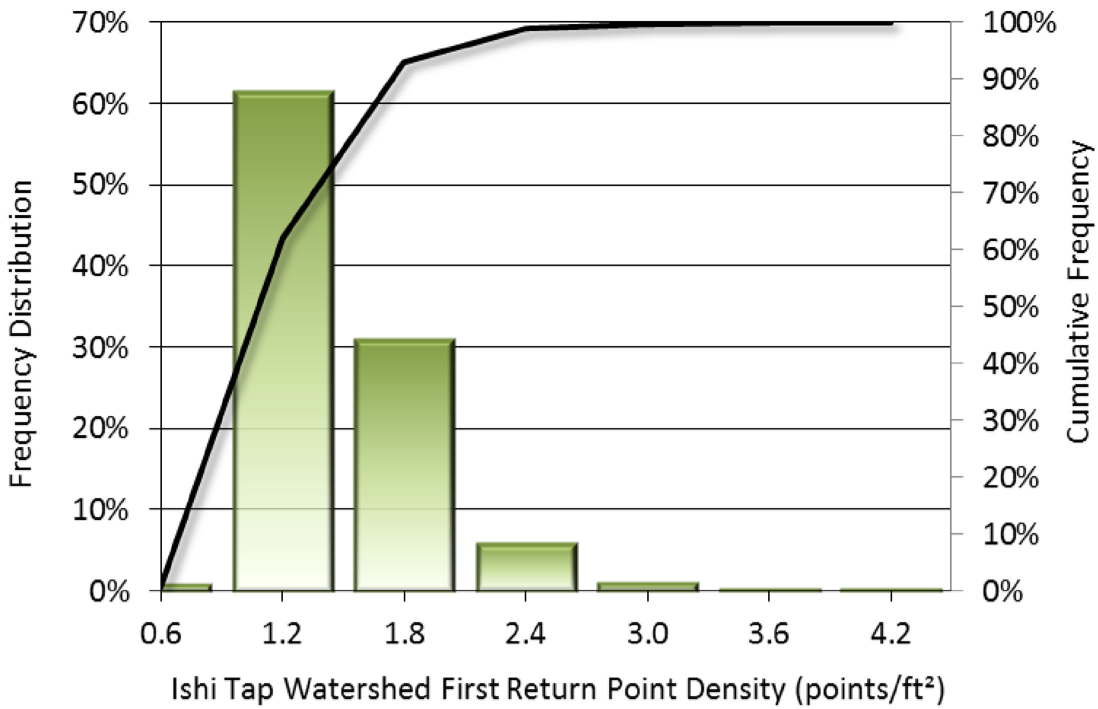


Figure 4: Frequency distribution of first return densities per 100 x 100 m cell in the Ishi Tap Watershed AOI

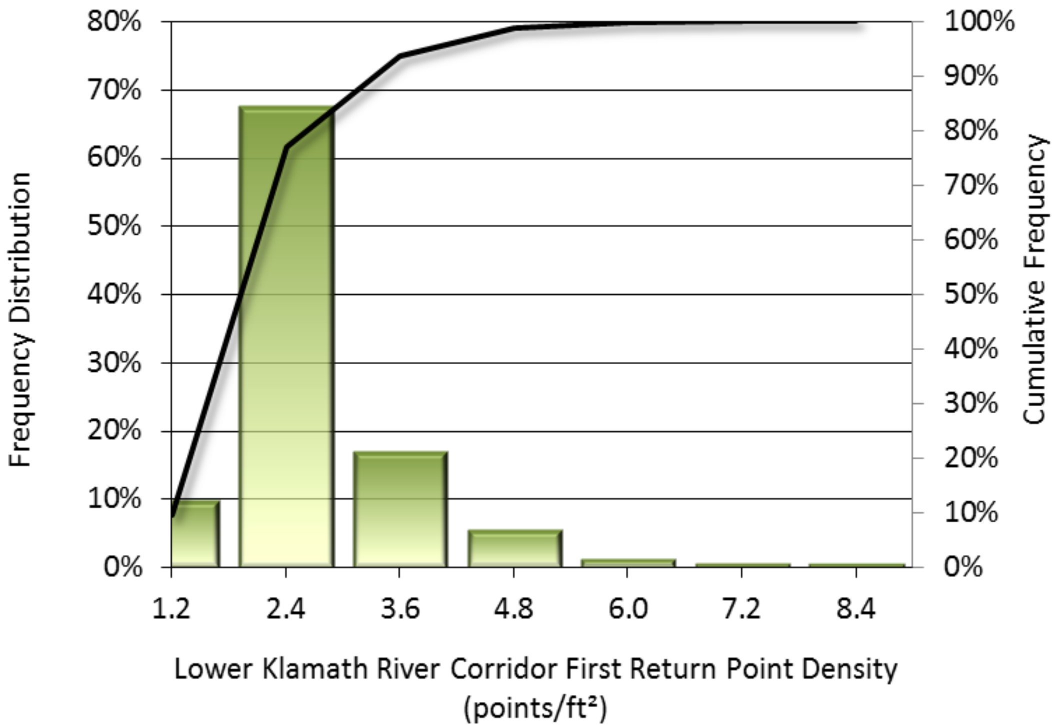


Figure 5: Frequency distribution of first return densities per 100 x 100 m cell in the Lower Klamath River Corridor AOI

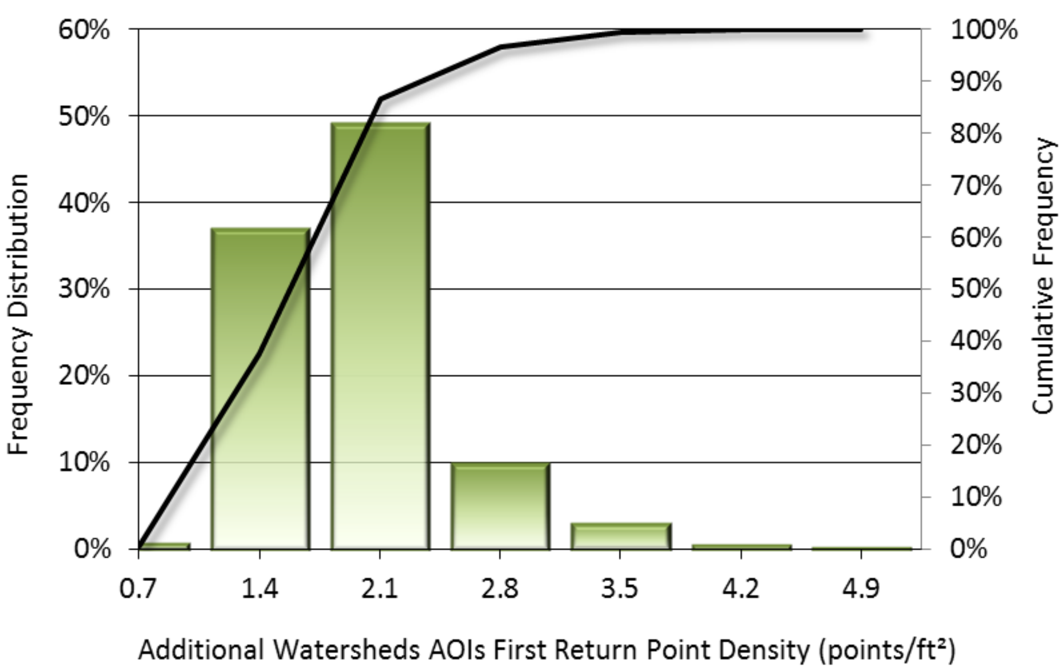


Figure 6: Frequency distribution of first return densities per 100 x 100 m cell in the Additional Watersheds AOIs

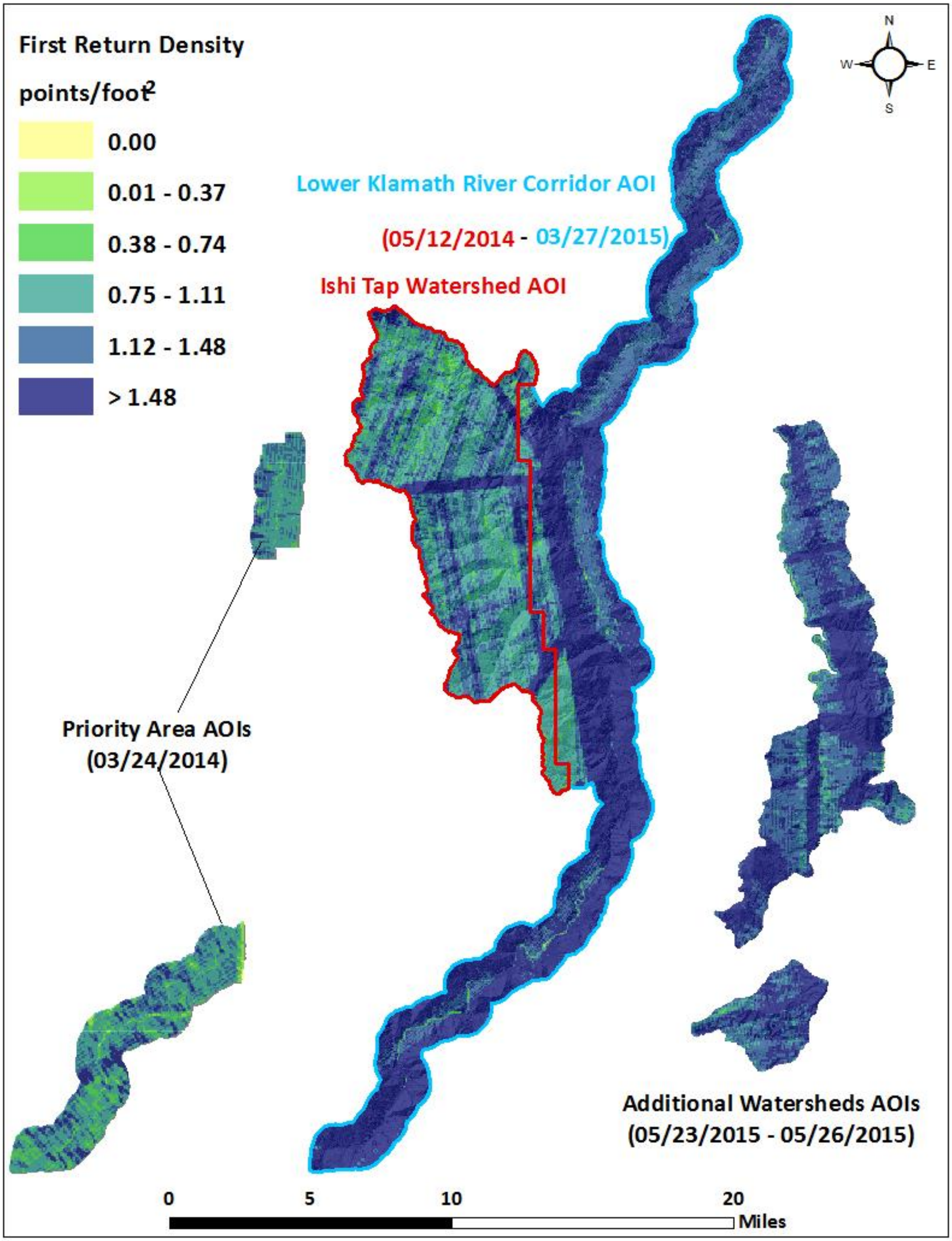


Figure 7: First return density map for the Lower Klamath Watersheds site (100 m x 100 m cells)

Ground Classified Point Density

The density of ground-classified LiDAR returns was also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In vegetated areas, fewer pulses may penetrate the canopy, resulting in lower ground density.

The average ground classified return density of LiDAR data for each of the AOIs in the Lower Klamath Watersheds project is displayed in Table 13. The statistical and spatial distributions of first classified ground return densities per 100 m x 100 m cell are portrayed in Figure 8 through Figure 12.

Table 13: Average Ground Return LiDAR point densities

Classification	Point Density			
	Priority Areas	Ishi Tap Watershed	Lower Klamath River Corridor	Additional Watersheds
Ground Classified Return Density	0.11 points/ft^2 1.14 points/m^2	0.14 points/ft^2 1.49 points/m^2	0.20 points/ft^2 2.17 points/m^2	0.10 points/ft^2 1.03 points/m^2

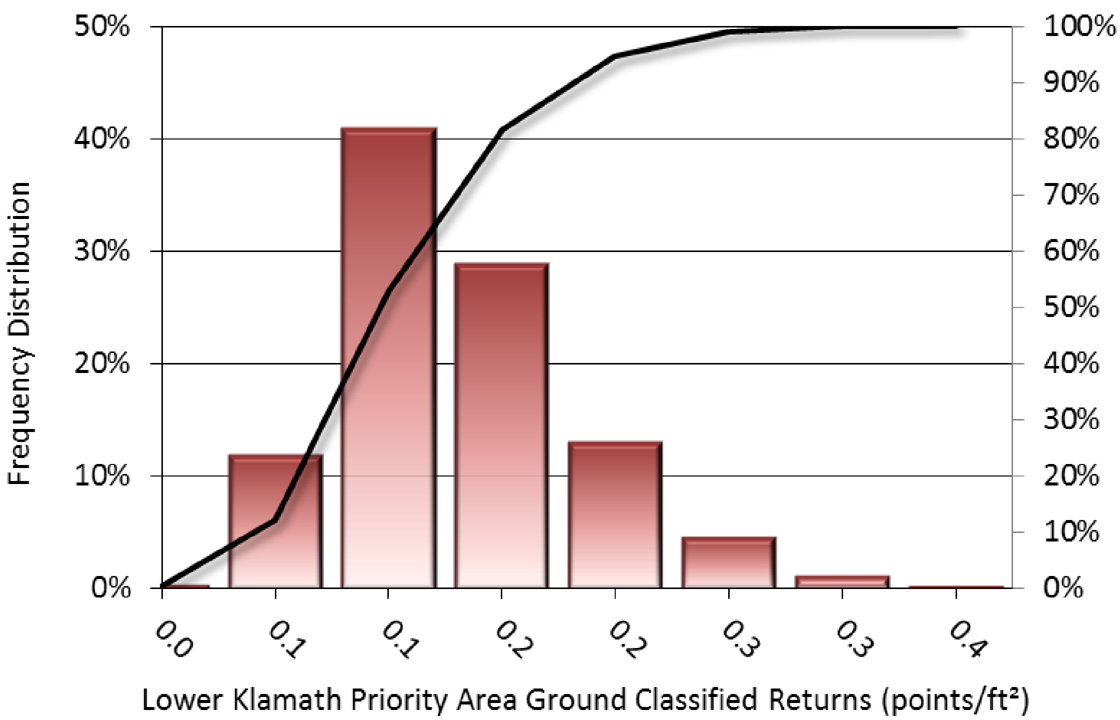


Figure 8: Frequency distribution of ground classified return densities per 100 x 100 m cell in the Priority Area AOIs

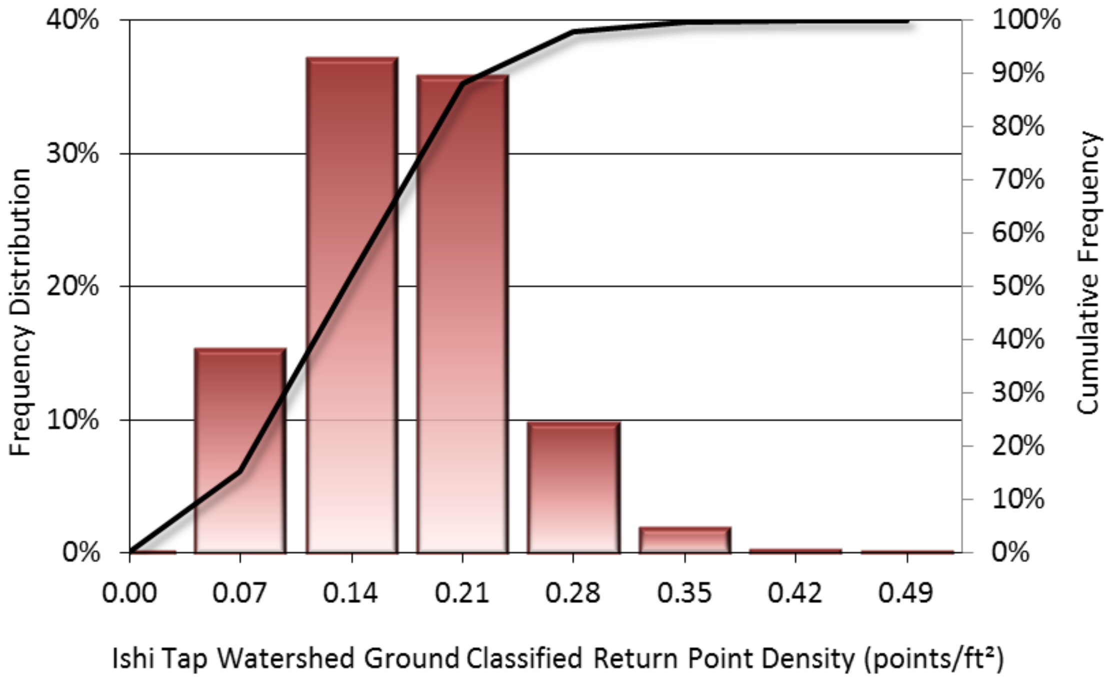


Figure 9: Frequency distribution of ground classified return densities per 100 x 100 m cell in the Ishi Tap Watershed AOI

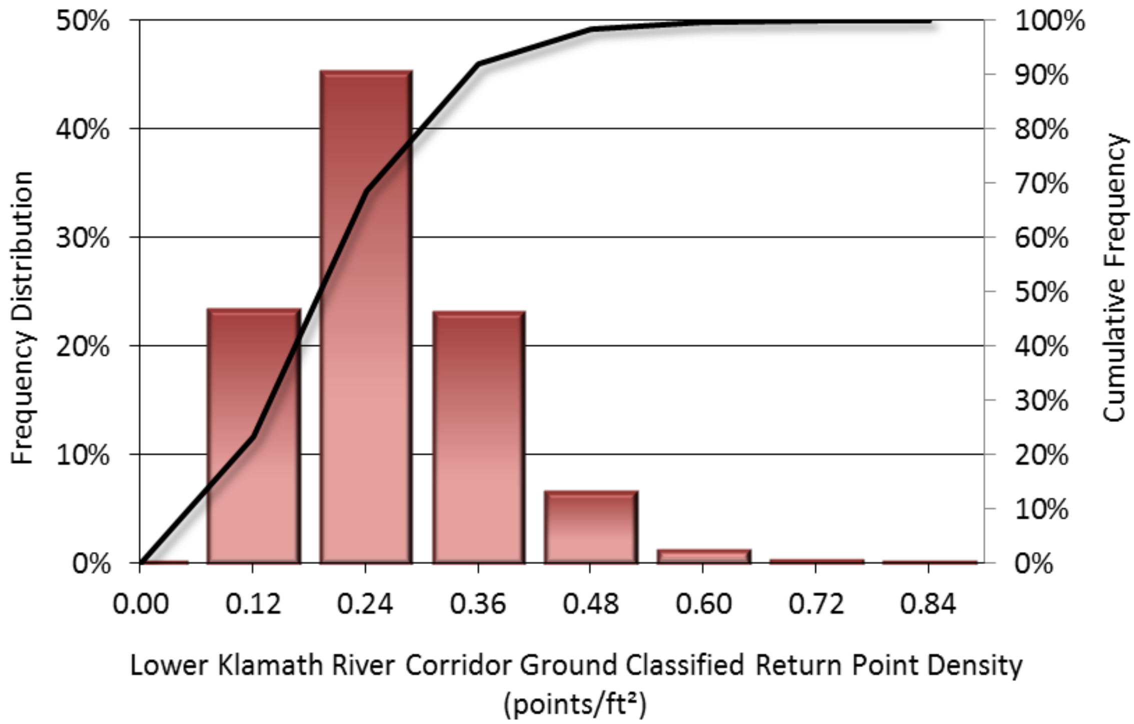


Figure 10: Frequency distribution of ground classified return densities per 100 x 100 m cell in the Lower Klamath River Corridor AOI

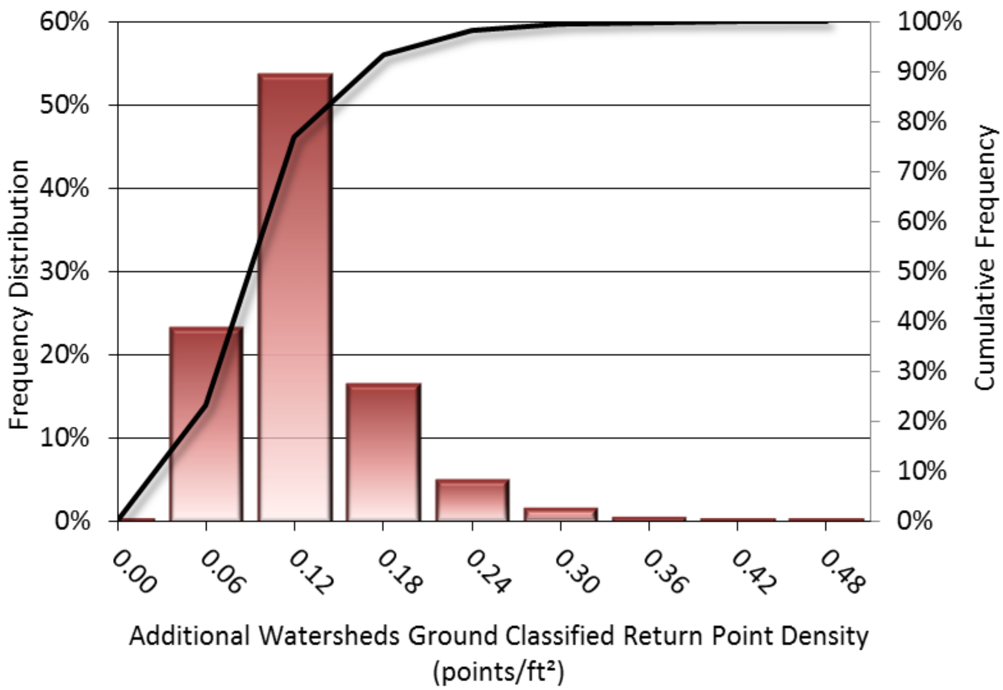


Figure 11: Frequency distribution of ground classified return densities per 100 x 100 m cell in the Priority AOIs

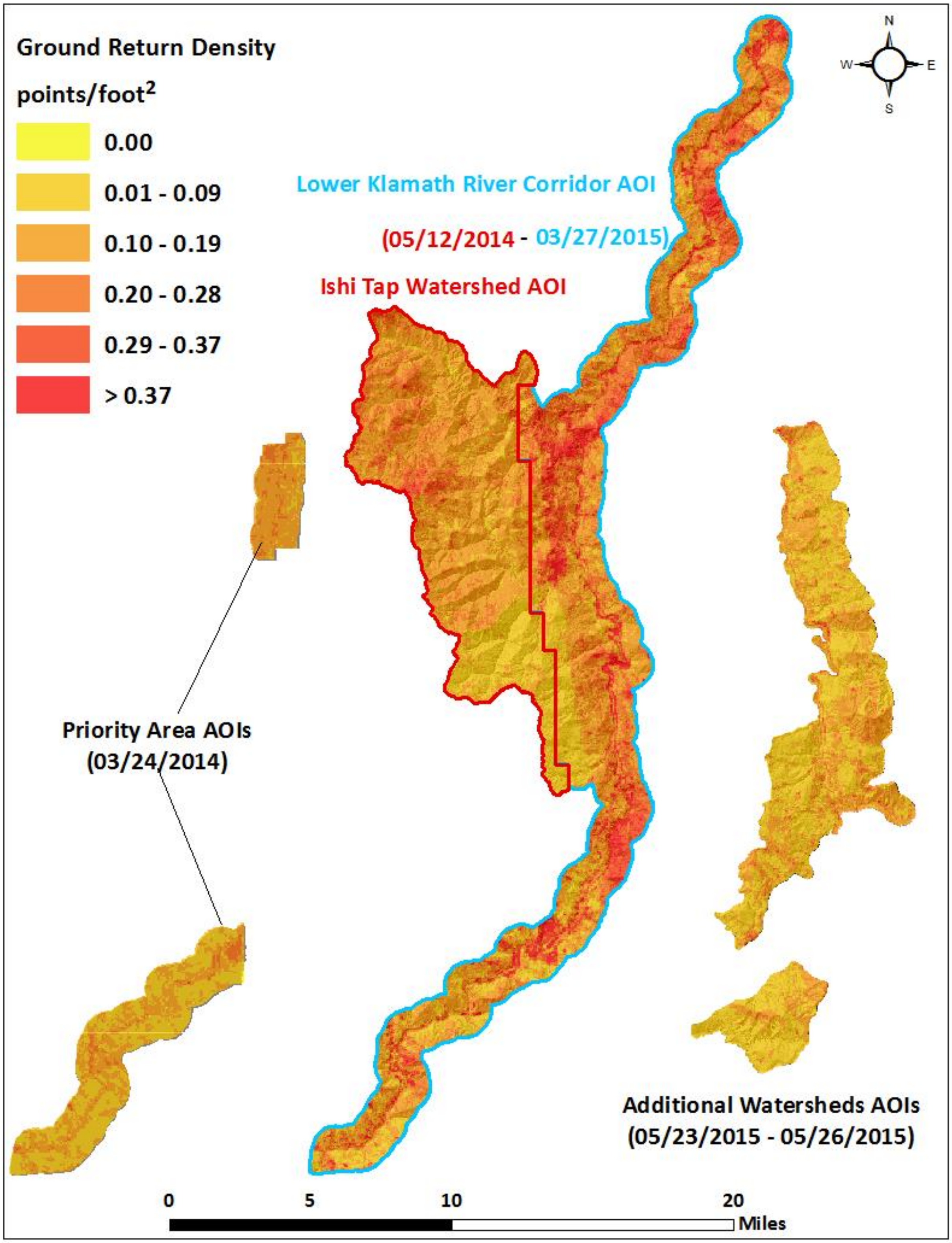


Figure 12: Ground density map for the Lower Klamath Watersheds site (100 m x 100 m cells)

LiDAR Accuracy Assessments

The accuracy of the LiDAR data collection can be described in terms of absolute accuracy (the consistency of the data with external data sources) and relative accuracy (the consistency of the dataset with itself). See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

LiDAR Absolute Accuracy

Absolute accuracy compares known RTK ground control point data collected on open, bare earth surfaces with level slope (<20°) to the triangulated surface generated by the LiDAR points. Absolute accuracy is a measure of the accuracy of LiDAR point data in open areas where the LiDAR system has a high probability of measuring the ground surface and was evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 14.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from ground survey point coordinates are also considered during accuracy assessment. These statistics assume the error for x, y and z is normally distributed, and therefore the skew and kurtosis of distributions are also considered when evaluating error statistics. For the Additional Watersheds AOI in the Lower Klamath Watersheds survey, 60 ground survey points were collected in total resulting in an average accuracy of 0.029 feet (0.009 meters). Absolute accuracy statistics for all AOIs are shown in Table 14, and Figure 13 through Figure 16.

Table 14: Absolute accuracy

Absolute Accuracy				
	Priority Area	Ishi Tap Watershed	Lower Klamath River Corridor	Additional Watersheds
Sample	383 points	806 points	481 points	60 points
1.96*RMSE	0.189 ft 0.057 m	0.218 ft 0.066 m	0.218 ft 0.066 m	0.183 ft 0.056 m
Average	-0.009 ft -0.003 m	-0.023 ft -0.007 m	-0.048 ft -0.014 m	0.029 ft 0.009 m
Median	-0.013 ft -0.004 m	-0.026 ft -0.008 m	-0.049 ft -0.015 m	0.043 ft 0.013 m
RMSE	0.096 ft 0.029 m	0.111 ft 0.034 m	0.111 ft 0.034 m	0.093 ft 0.028 m
Standard Deviation (1σ)	0.096 ft 0.029 m	0.109 ft 0.033 m	0.101 ft 0.066 m	0.027 ft 0.089 m

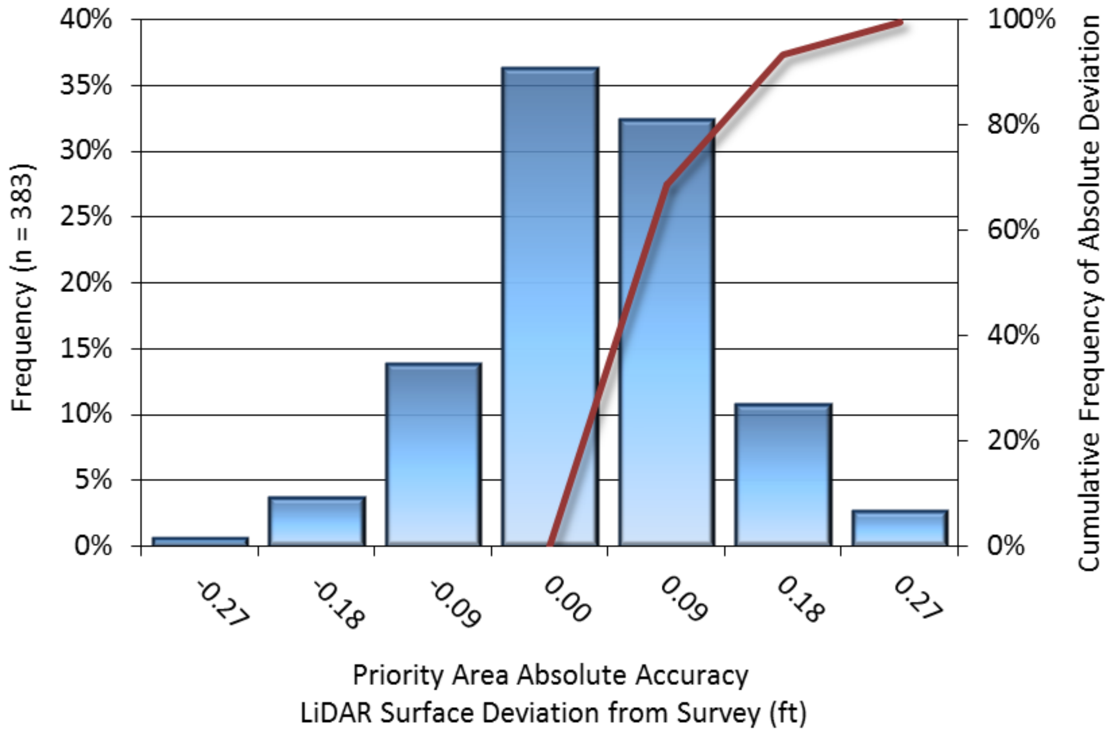


Figure 13: Frequency histogram for LiDAR surface deviation from ground survey point values in the Priority Area AOI

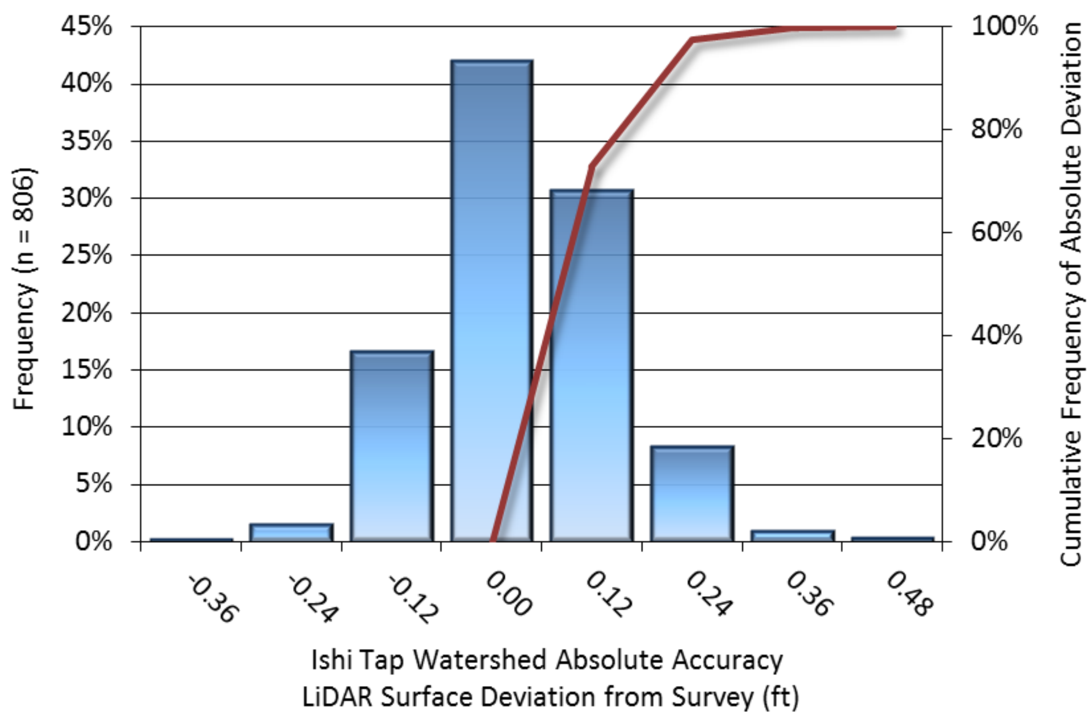


Figure 14: Frequency histogram for LiDAR surface deviation from ground survey point values in the Ishi Tap Watershed AOI

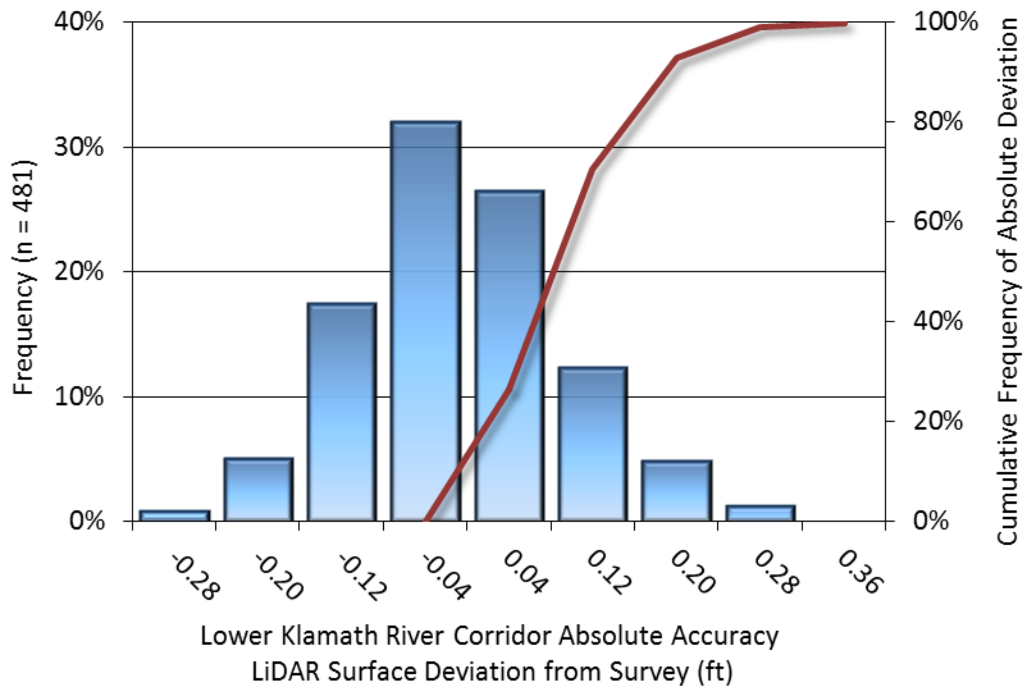


Figure 15: Frequency histogram for LiDAR surface deviation from ground survey point values in the Lower Klamath River Corridor AOI

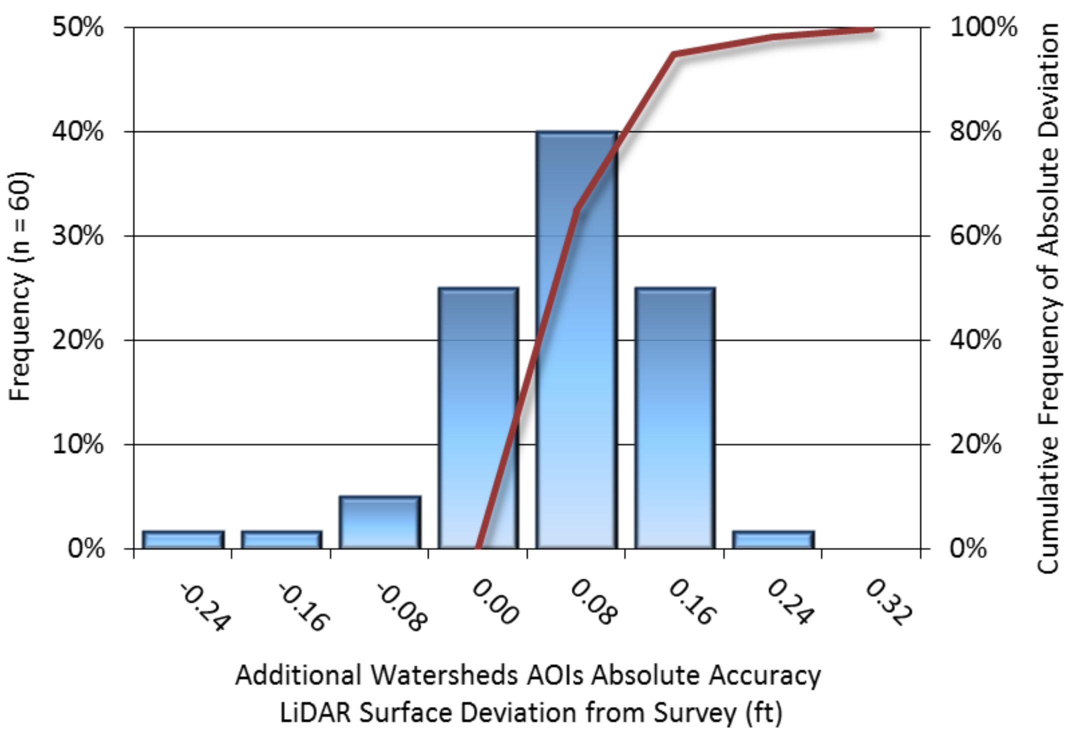


Figure 16: Frequency histogram for LiDAR surface deviation from ground survey point values in the Additional Watersheds AOI

LiDAR Vertical Relative Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the LiDAR system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the Additional Watersheds AOI in the Lower Klamath Watersheds LiDAR project was 0.187 feet (0.057 meters). Relative accuracy statistics for all AOIs are shown in Table 15, and Figure 17 through Figure 20.

Table 15: Relative accuracy

Relative Accuracy				
	Priority Area	**Ishi Tap Watershed**	**Lower Klamath River Corridor**	**Additional Watersheds**
Sample	54 surfaces	271 surfaces	360 surfaces	186 surfaces
Average	0.212 ft 0.065 m	0.229 ft 0.070 m	0.210 ft 0.064 m	0.187 ft 0.057 m
Median	0.218 ft 0.066 m	0.223 ft 0.068 m	0.202 ft 0.062 m	0.184 ft 0.056 m
RMSE	0.221 ft 0.067 m	0.229 ft 0.070 m	0.199 ft 0.061 m	0.197 ft 0.060 m
Standard Deviation (1σ)	0.025 ft 0.007 m	0.031 ft 0.009 m	0.046 ft 0.014 m	0.037 ft 0.011 m
1.96σ	0.048 ft 0.015 m	0.060 ft 0.018 m	0.090 ft 0.028 m	0.073 ft 0.022 m

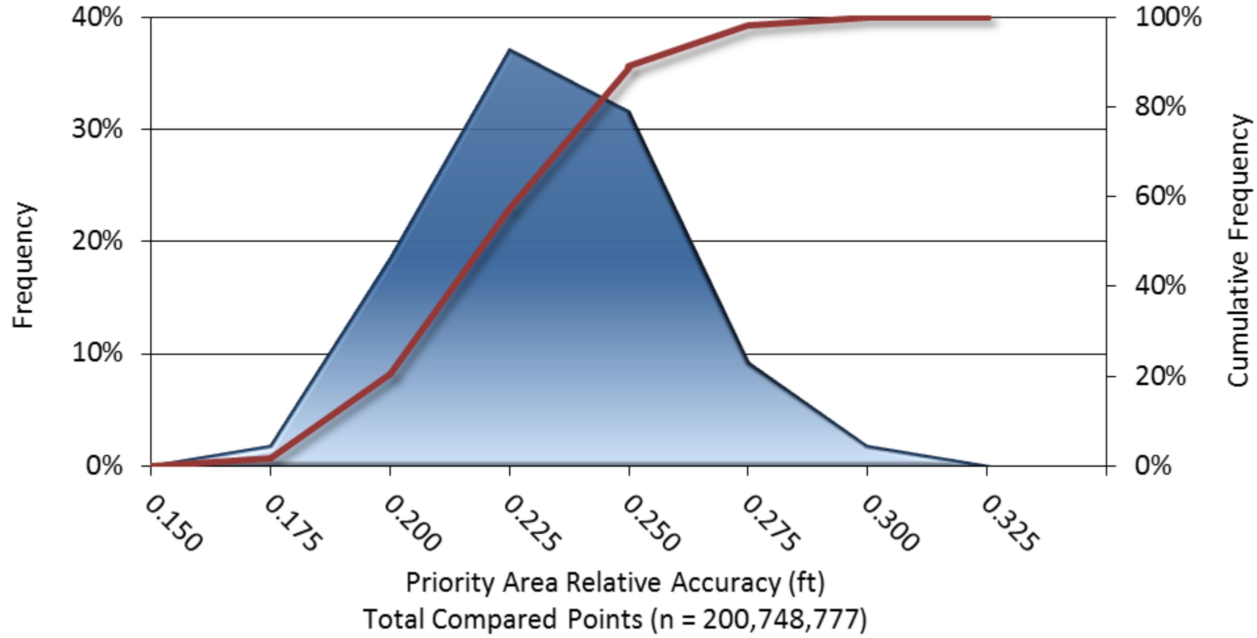


Figure 17: Frequency plot for relative vertical accuracy between flight lines in the Priority Area AOIs

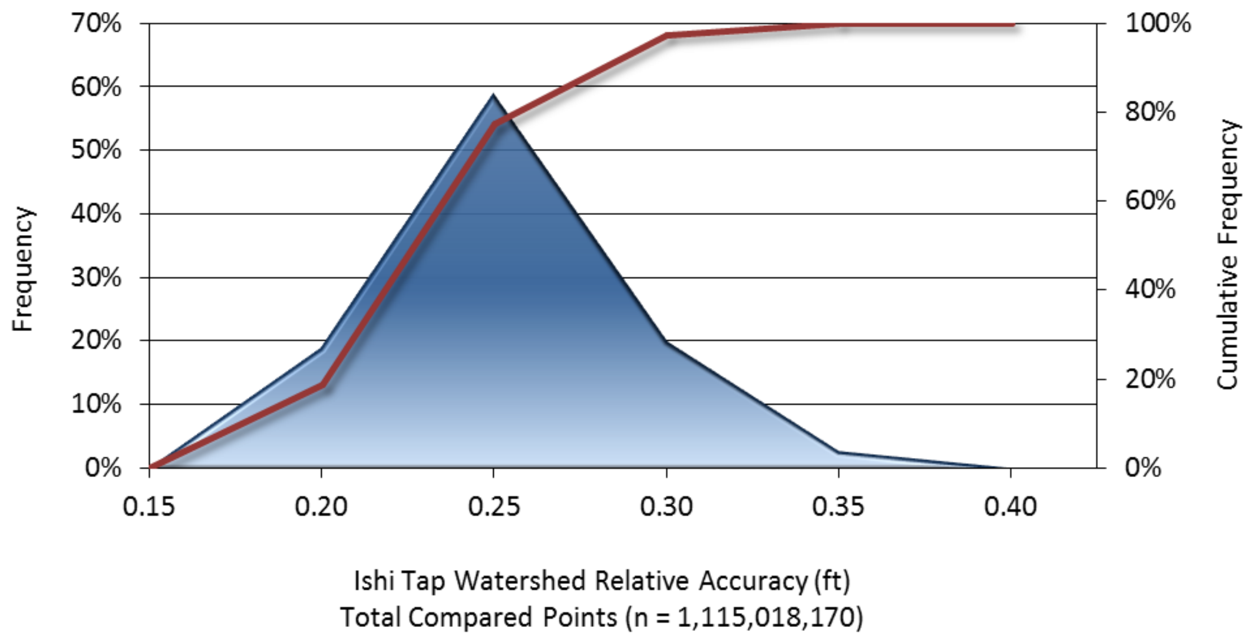


Figure 18: Frequency plot for relative vertical accuracy between flight lines in the Ishi Tap Watershed AOI

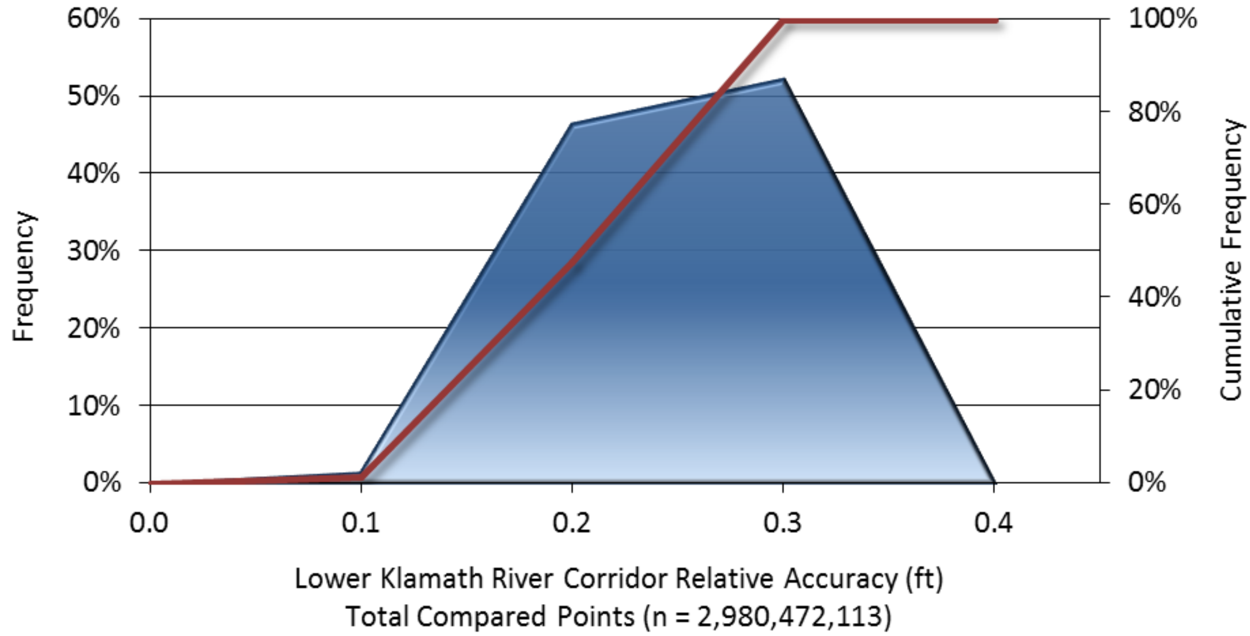


Figure 19: Frequency plot for relative vertical accuracy between flight lines in the Lower Klamath River Corridor AOI

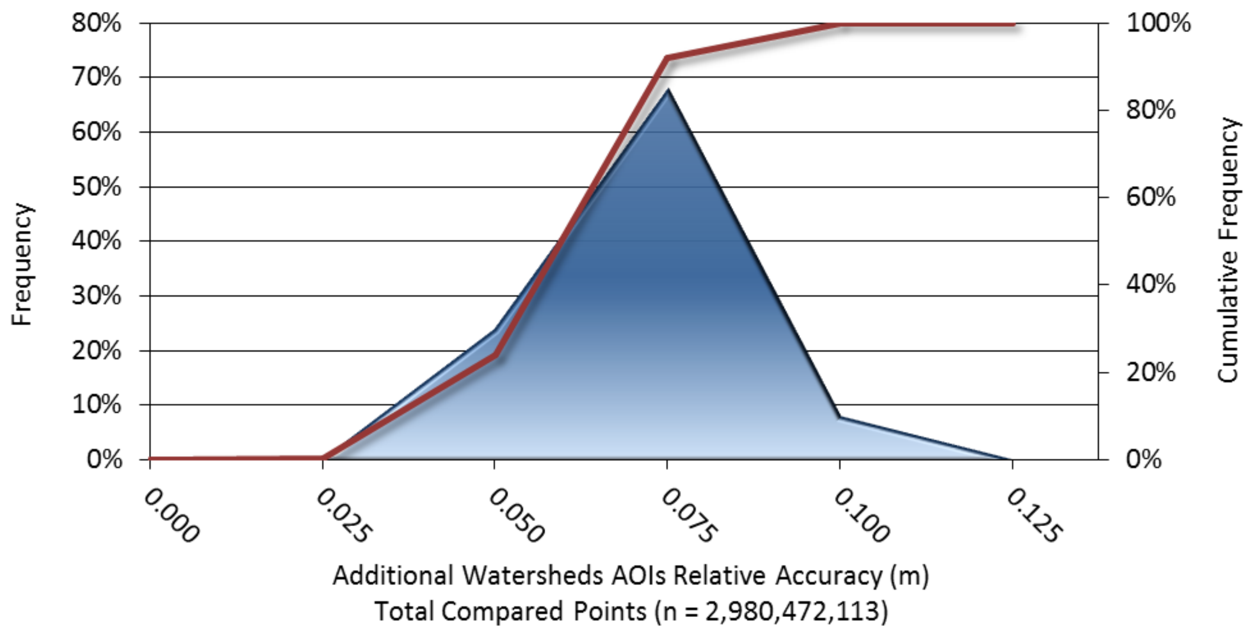


Figure 20: Frequency plot for relative vertical accuracy between flight lines in the Additional Watersheds AOIs

Digital Imagery Accuracy Assessment

Image accuracy was measured by air target locations and independent ground survey points. Air target GPS points were measured against the placement of the air target in the imagery. In addition, ground survey points were identified on the LiDAR intensity images in areas of clear visibility. Once the ground survey points were identified in the intensity images the exact spot was identified in the orthophotography and the displacement was recorded for further statistical analysis.

The circular standard error (CSE) for the Lower Klamath River Corridor site was 0.88 feet measured by ground survey points and 0.51 feet measured by air targets. Circular standard error was approximated based on the FGDC National Standard for Spatial Data Accuracy for horizontal accuracy[3]. The CSE (at 39.35% standard) was computed as follows:

where $RMSE_x = RMSE_y$: $CSE = 1.7308 * RMSE_{xy}$

Table 16 presents the complete photo accuracy statistics and Figure 21 contains a scatterplot showing congruence between LiDAR intensity images and orthophotos in aerial target locations.

Table 16: Orthophotography accuracy statistics for Lower Klamath River Corridor AOI

Lower Klamath River Corridor Photo Accuracy							
		Check Points$_x$	Check Points$_y$	Check Points$_{xy}$	Air Targets$_x$	Air Targets$_y$	Air Targets$_{xy}$
Count		n = 24			n = 2		
Mean	*ft*	-0.095	0.304	0.319	-0.161	-0.474	0.501
	m	-0.029	0.093	0.097	-0.049	-0.144	0.153
RMSE	*ft*	0.532	0.606	0.807	0.257	0.500	0.562
	m	0.162	0.185	0.246	0.078	0.152	0.171
1σ	*ft*	0.535	0.536	0.757	0.283	0.225	0.361
	m	0.163	0.163	0.231	0.086	0.069	0.110
1.96σ	*ft*	1.049	1.050	1.484	0.554	0.441	0.708
	m	0.320	0.320	0.452	0.169	0.134	0.216

[3] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.3-1998). Part 3: National Standard for Spatial Data Accuracy, Appendix 3-A, page 3-10. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3

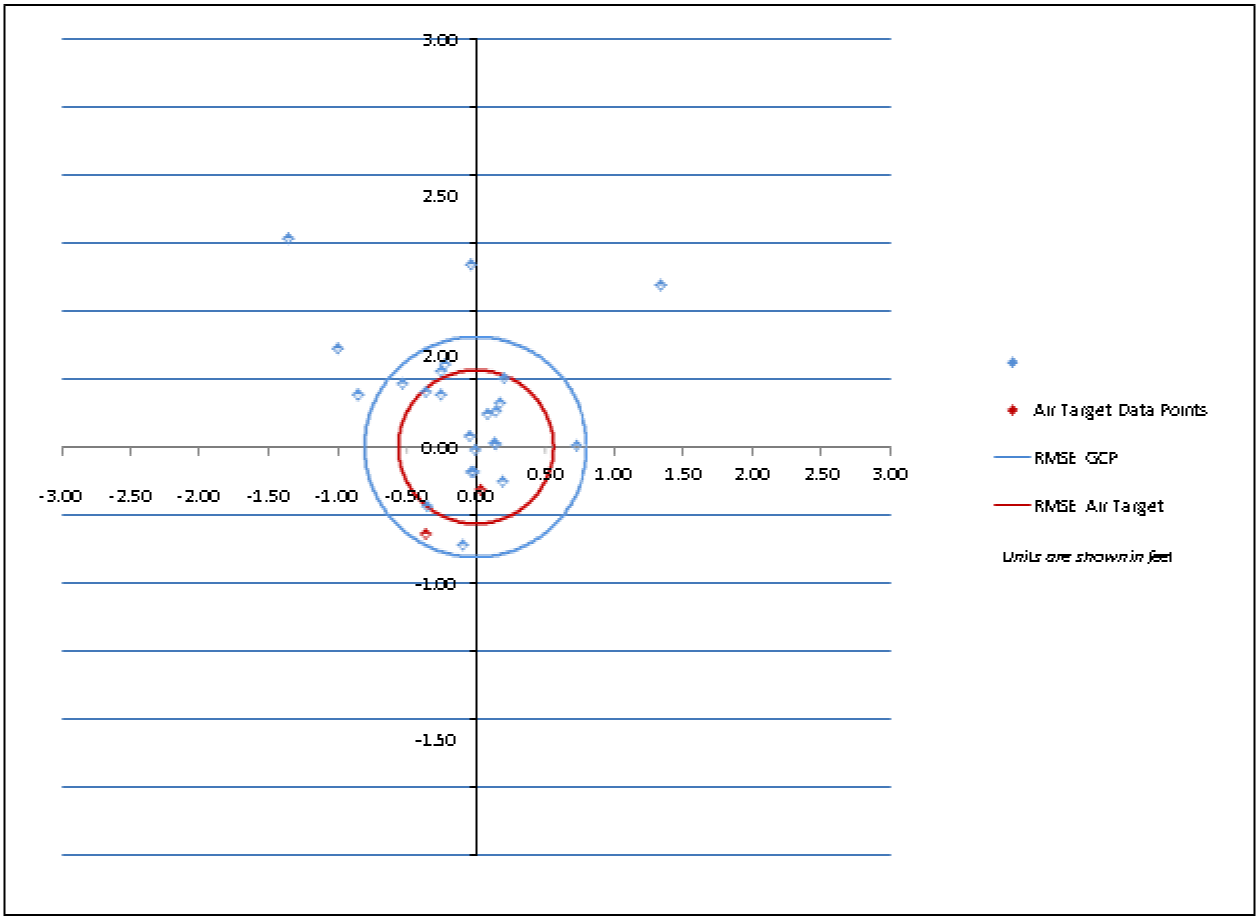


Figure 21: Scatterplot displaying the XY deviation of aerial targets aligned with the orthophoto imagery when compared against the LiDAR intensity images.

CERTIFICATIONS

Quantum Spatial provided LiDAR services for the Lower Klamath River Corridor project as described in this report.

I, Christopher Glantz, being duly registered as a Professional Land Surveyor in and by the state of California, hereby certify that the methodologies, static GNSS occupations used during airborne flights, and ground survey point collection were performed using commonly accepted Standard Practices. Field work conducted for this report was conducted between March 22, 2014 and March 27, 2015.

Accuracy statistics shown in the Accuracy Section of this Report have been reviewed by me and found to meet the "National Standard for Spatial Data Accuracy".

7/24/2015

Christopher Glantz, PLS
Professional Land Surveyor
Quantum Spatial, Inc.
Corvallis, OR 97333

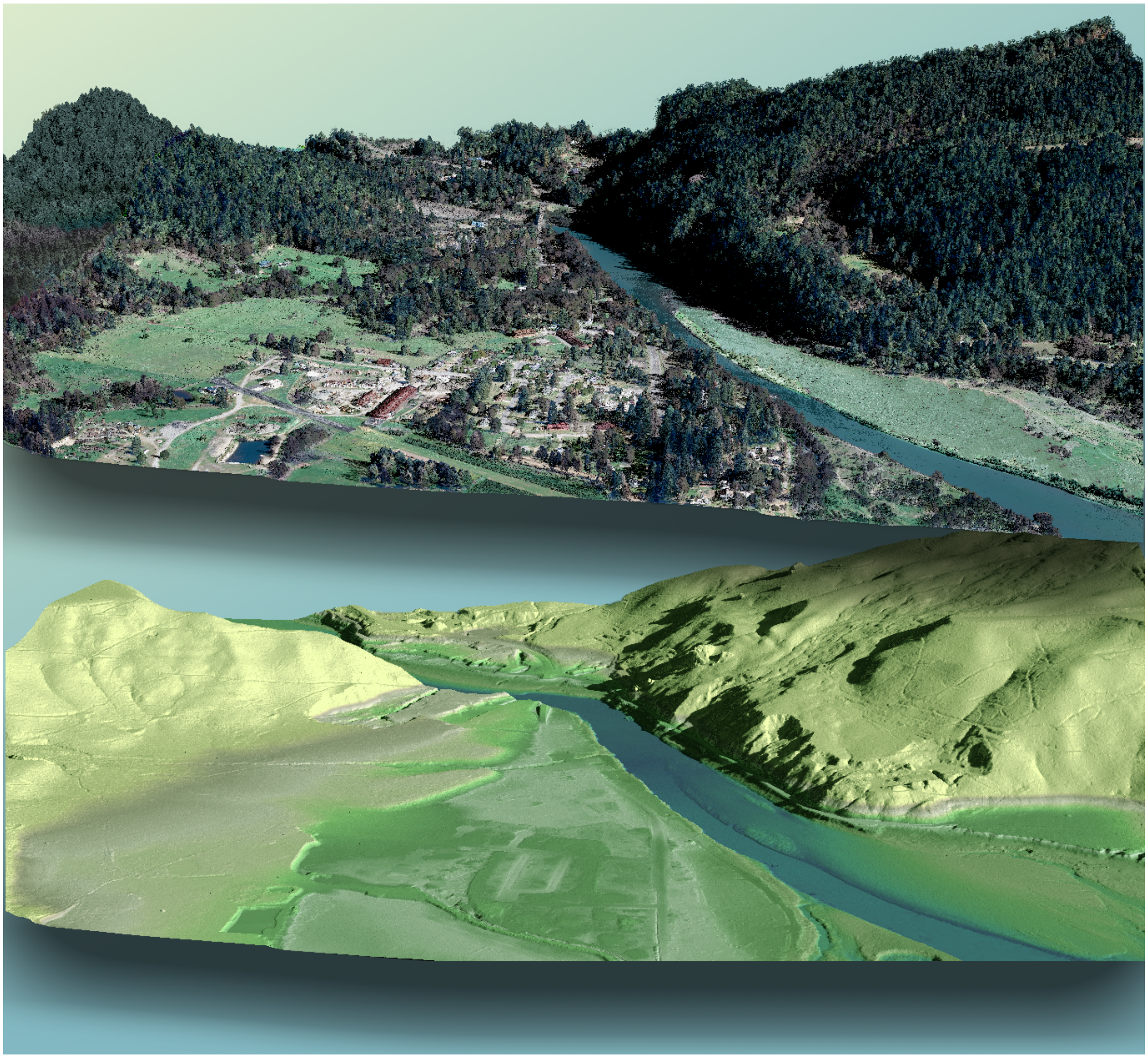


Figure 22: View looking northeast over Orleans, California. The images were created with the gridded LiDAR surface colored by elevation with the 3D LiDAR point cloud and RGB orthoimagery overlaid in the top image.

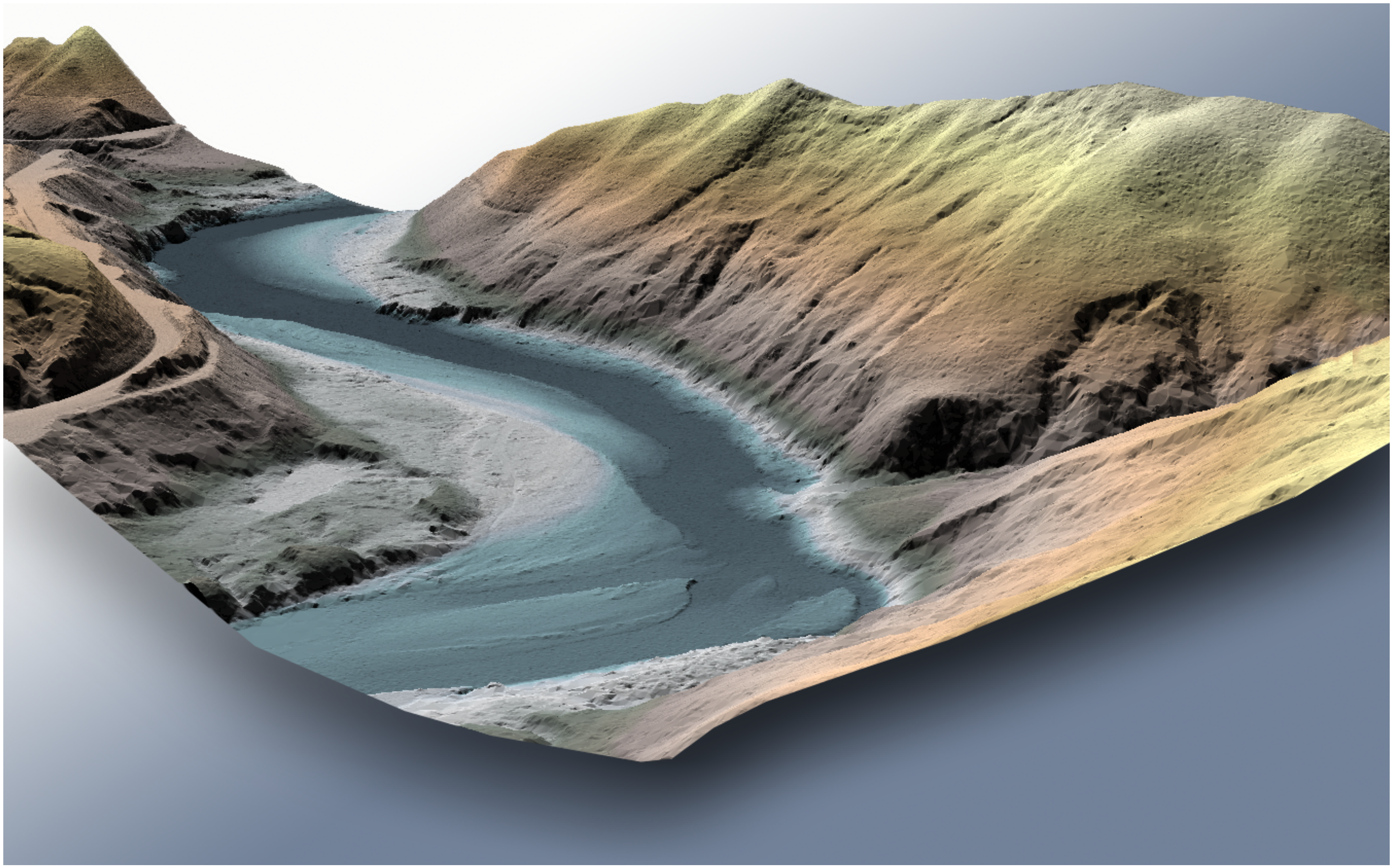


Figure 23: View looking East over the Klamath River located west of Marble Mountain Ranch. The image was created from the gridded LiDAR surface colored by elevation.

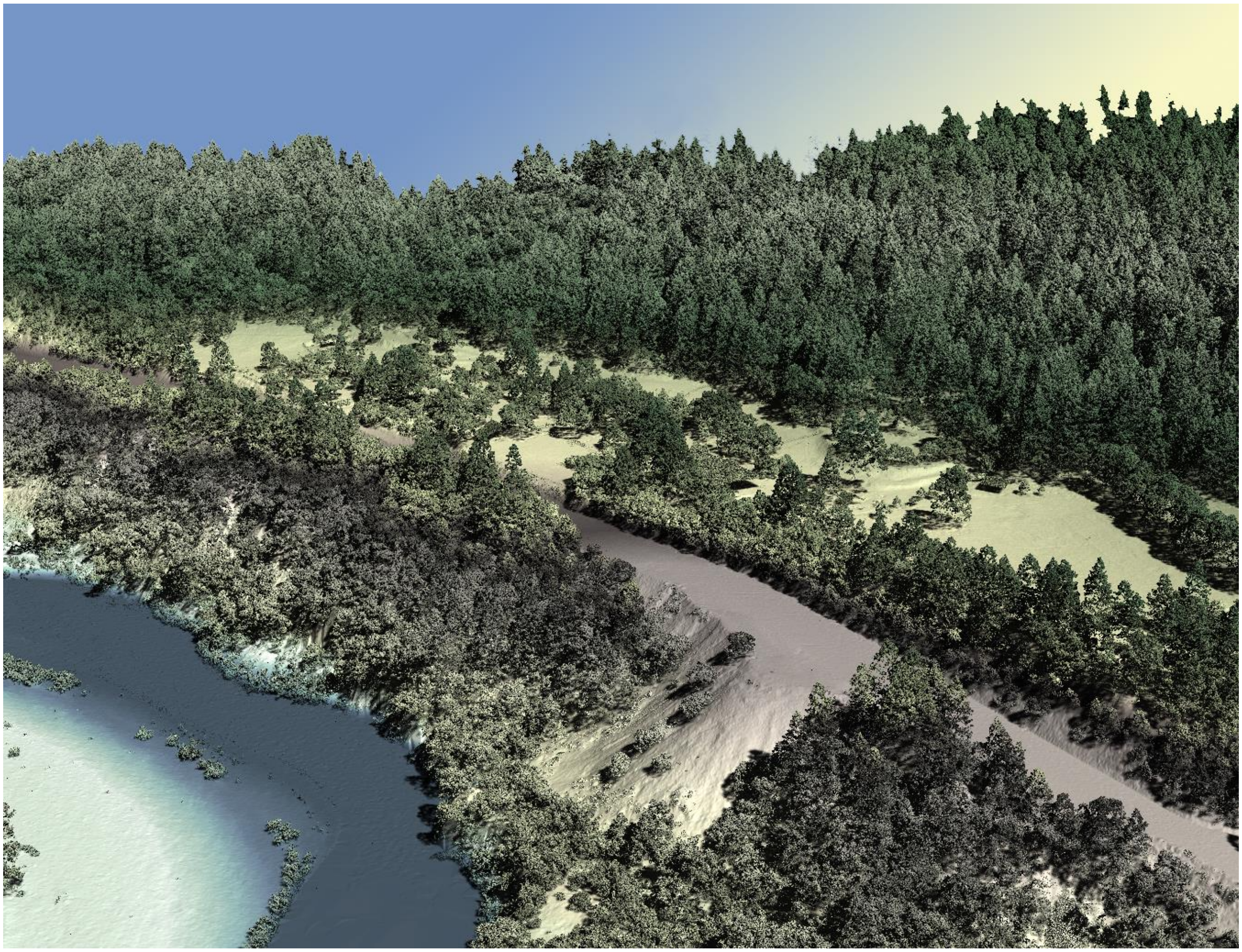


Figure 24: View of a hillside showing regenerated clear-cuts. The image was created with the gridded LiDAR surface colored by elevation and overlaid with the 3D LiDAR point cloud.

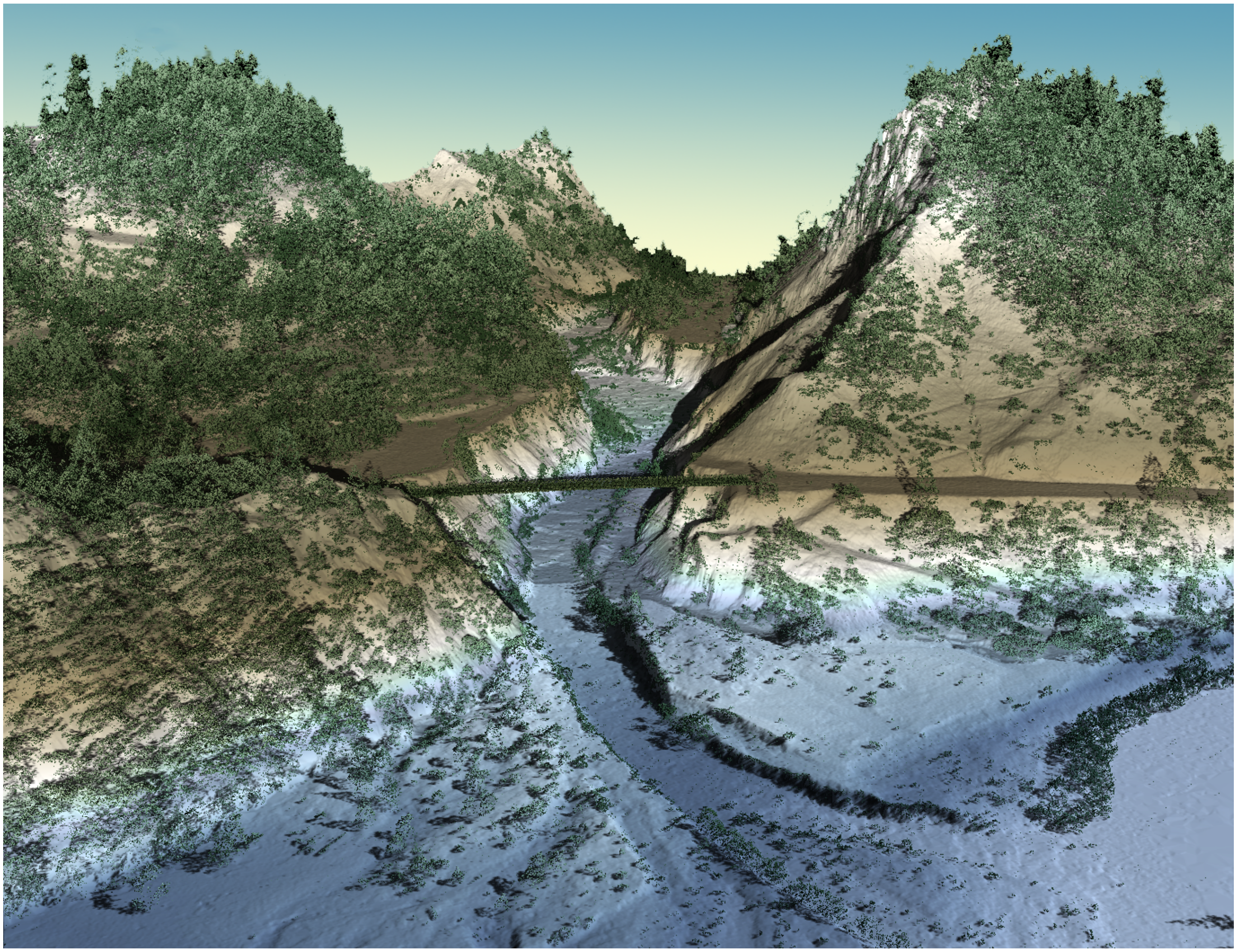


Figure 25: View looking northwest toward the Bluff Creek Bridge. The image was created from the gridded LiDAR surface colored by elevation and overlaid with the 3D LiDAR point cloud.

GLOSSARY

1-sigma (σ) Absolute Deviation: Value for which the data are within one standard deviation (approximately 68th percentile) of a normally distributed data set.

1.96 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set, based on the FGDC standards for Fundamental Vertical Accuracy (FVA) reporting.

Accuracy: The statistical comparison between known (surveyed) points and laser points. Typically measured as the standard deviation (sigma σ) and root mean square error (RMSE).

> **Absolute Accuracy:** The vertical accuracy of LiDAR data is described as the mean and standard deviation (sigma σ) of divergence of LiDAR point coordinates from ground survey point coordinates. To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y and z are normally distributed, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. Affected by system attitude offsets, scale and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the LiDAR system is well calibrated, the line-to-line divergence is low (<10 cm).
>
> **Root Mean Square Error (RMSE):** A statistic used to approximate the difference between real-world points and the LiDAR points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

Data Density: A common measure of LiDAR resolution, measured as points per square meter.

Digital Elevation Model (DEM): File or database made from surveyed points, containing elevation points over a contiguous area. Digital terrain models (DTM) and digital surface models (DSM) are types of DEMs. DTMs consist solely of the bare earth surface (ground points), while DSMs include information about all surfaces, including vegetation and man-made structures.

Intensity Values: The peak power ratio of the laser return to the emitted laser, calculated as a function of surface reflectivity.

Nadir: A single point or locus of points on the surface of the earth directly below a sensor as it progresses along its flight line.

Overlap: The area shared between flight lines, typically measured in percent. 100% overlap is essential to ensure complete coverage and reduce laser shadows.

Pulse Rate (PR): The rate at which laser pulses are emitted from the sensor; typically measured in thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the number of wave forms (i.e., echos) reflected back to the sensor. Portions of the wave form that return first are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

Real-Time Kinematic (RTK) Survey: A type of surveying conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

Post-Processed Kinematic (PPK) Survey: GPS surveying is conducted with a GPS rover collecting concurrently with a GPS base station set up over a known monument. Differential corrections and precisions for the GNSS baselines are computed and applied after the fact during processing. This type of ground survey is accurate to 1.5 cm or less.

Scan Angle: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase.

Native LiDAR Density: The number of pulses emitted by the LiDAR system, commonly expressed as pulses per square meter.

Relative Accuracy Calibration Methodology:

Manual System Calibration: Calibration procedures for each mission require solving geometric relationships that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.

Automated Attitude Calibration: All data were tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and heading) and scale were solved for each individual mission and applied to respective mission datasets. The data from each mission were then blended when imported together to form the entire area of interest.

Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

LiDAR accuracy error sources and solutions:

Type of Error	Source	Post Processing Solution
GPS (Static/Kinematic)	Long Base Lines	None
	Poor Satellite Constellation	None
	Poor Antenna Visibility	Reduce Visibility Mask
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings
	Inaccurate System	None
Laser Noise	Poor Laser Timing	None
	Poor Laser Reception	None
	Poor Laser Power	None
	Irregular Laser Shape	None

Operational measures taken to improve relative accuracy:

Low Flight Altitude: Terrain following was employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (about 1/3000th AGL flight altitude).

Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return (i.e., intensity) is a function of laser emission power, laser footprint, flight altitude and the reflectivity of the target. While surface reflectivity cannot be controlled, laser power can be increased and low flight altitudes can be maintained.

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of ±15^{o} from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.

Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). Before each flight, the PDOP was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1 second epochs was utilized and a maximum baseline length between the aircraft and the control points was less than 13 nm at all times.

Ground Survey: Ground survey point accuracy (<1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey points are distributed to the extent possible throughout multiple flight lines and across the survey area.

50% Side-Lap (100% Overlap): Overlapping areas are optimized for relative accuracy testing. Laser shadowing is minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the nadir portion of one flight line coincides with the swath edge portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

Opposing Flight Lines: All overlapping flight lines have opposing directions. Pitch, roll and heading errors are amplified by a factor of two relative to the adjacent flight line(s), making misalignments easier to detect and resolve.